Toward the detection of habitable planets

Contributions to the astrometric detection method and to the direct imaging technique

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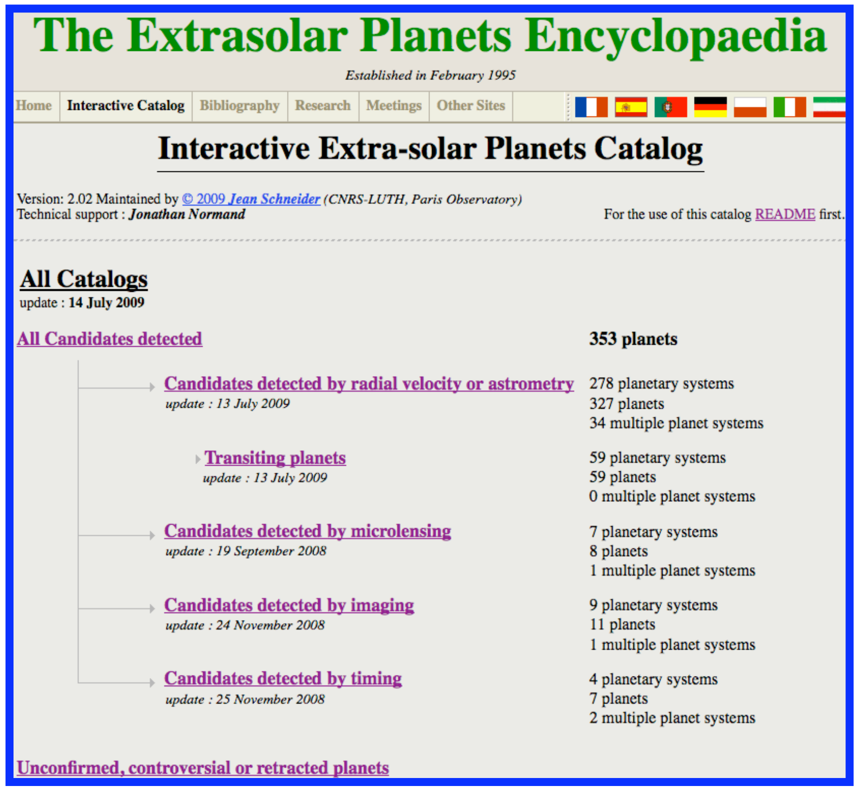
JPL Astrophysics and Exoplanet Science Seminars
July 16th, 2009

Outline

- Introduction
- Astrometric detection of planets with SIM
- Direct imaging technique: wavefront sensor
- Blue Dot: toward Habitable Earths
- Conclusion

Toward habitable terrestrial planets


The Extrasolar Planets Encyclopaedia

Established in February 1995

Home | Interactive Catalog | Bibliography | Research | Meetings | Other Sites

Interactive Extra-solar Planets Catalog

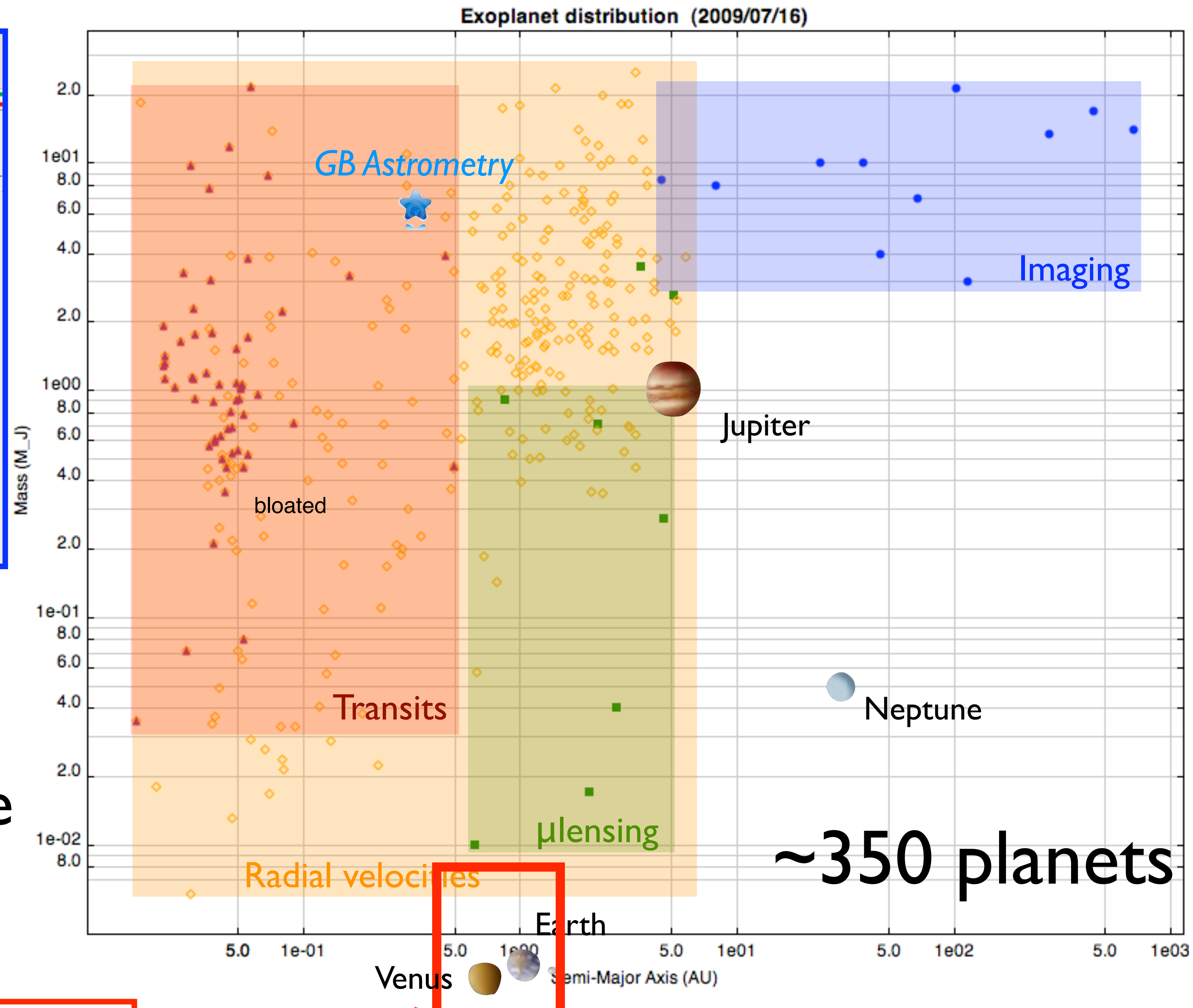
Version: 2.02 Maintained by © 2009 *Jean Schneider* (CNRS-LUTH, Paris Observatory)
Technical support : *Jonathan Normand*

For the use of this catalog README first.

All Catalogs
update : 14 July 2009

All Candidates detected	353 planets
Candidates detected by radial velocity or astrometry *update : 13 July 2009*	278 planetary systems 327 planets 34 multiple planet systems
Transiting planets *update : 13 July 2009*	59 planetary systems 59 planets 0 multiple planet systems
Candidates detected by microlensing *update : 19 September 2008*	7 planetary systems 8 planets 1 multiple planet systems
Candidates detected by imaging *update : 24 November 2008*	9 planetary systems 11 planets 1 multiple planet systems
Candidates detected by timing *update : 25 November 2008*	4 planetary systems 7 planets 2 multiple planet systems

Unconfirmed, controversial or retracted planets



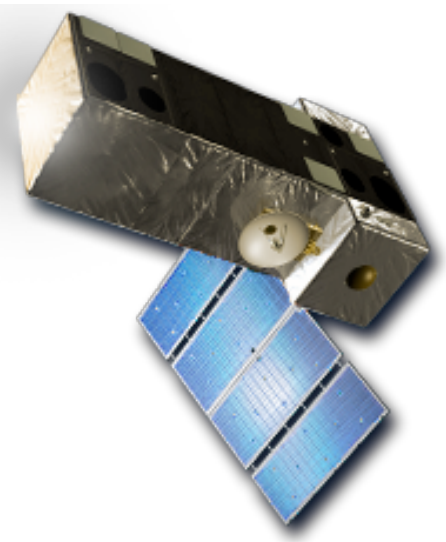
Ultimate goal is the search for biosignature in an Earth-like planet

Terrestrial planets in Habitable Zone

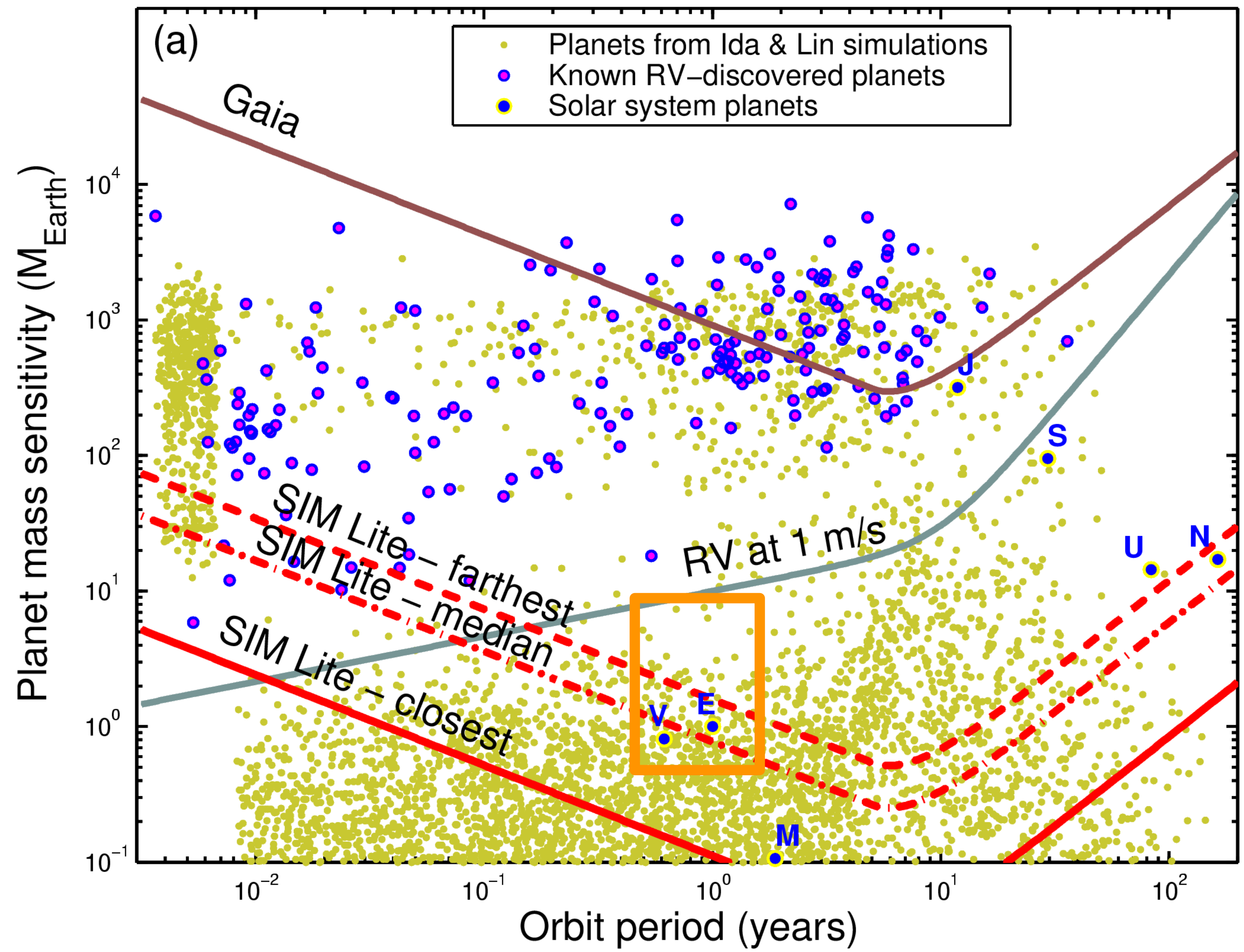
Astrometric detection

with J. Catanzarite, M. Shao, C. Zhai, V. Makarov, J. Lebreton, C. Beichman, W. Traub,...

Space Interferometry Mission



1. Deep planetary survey
2. Large planetary survey
3. Young planetary survey

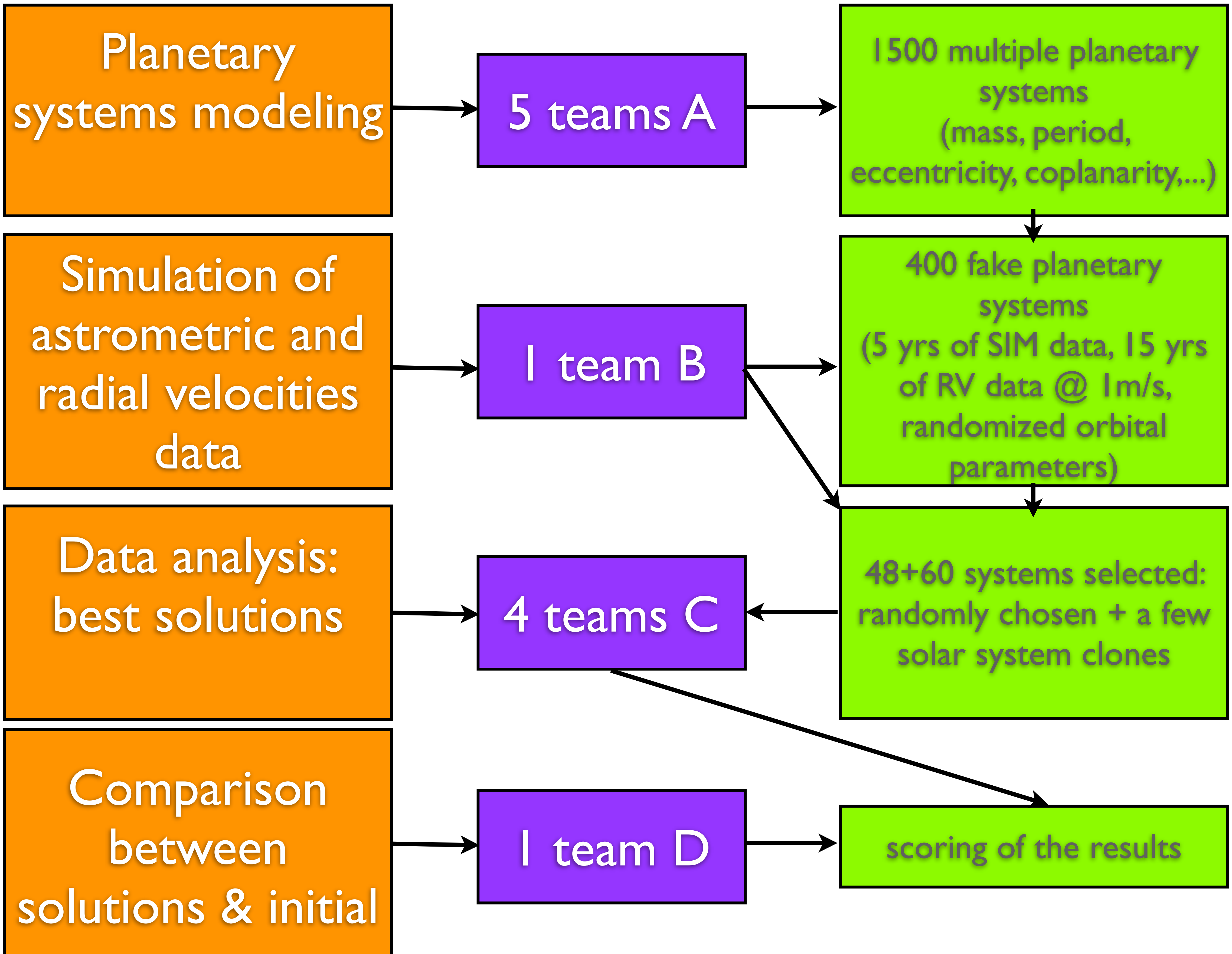


Is SIM able to detect Earth-like planets?

(G star at 10 pc)	Earth at 1 AU	Jupiter at 5 AU
Astrometry	0.3 μas	500 μas
RV	$0.1\ m.s^{-1}$	$13\ m.s^{-1}$

Mass sensitivity at mid-habitable zone	$1\ M_\oplus$	$2\ M_\oplus$	$3\ M_\oplus$
# of target stars that can be surveyed (1)	69	160	259

Double Blind Test study



Results from the double blind test

Detectable means:

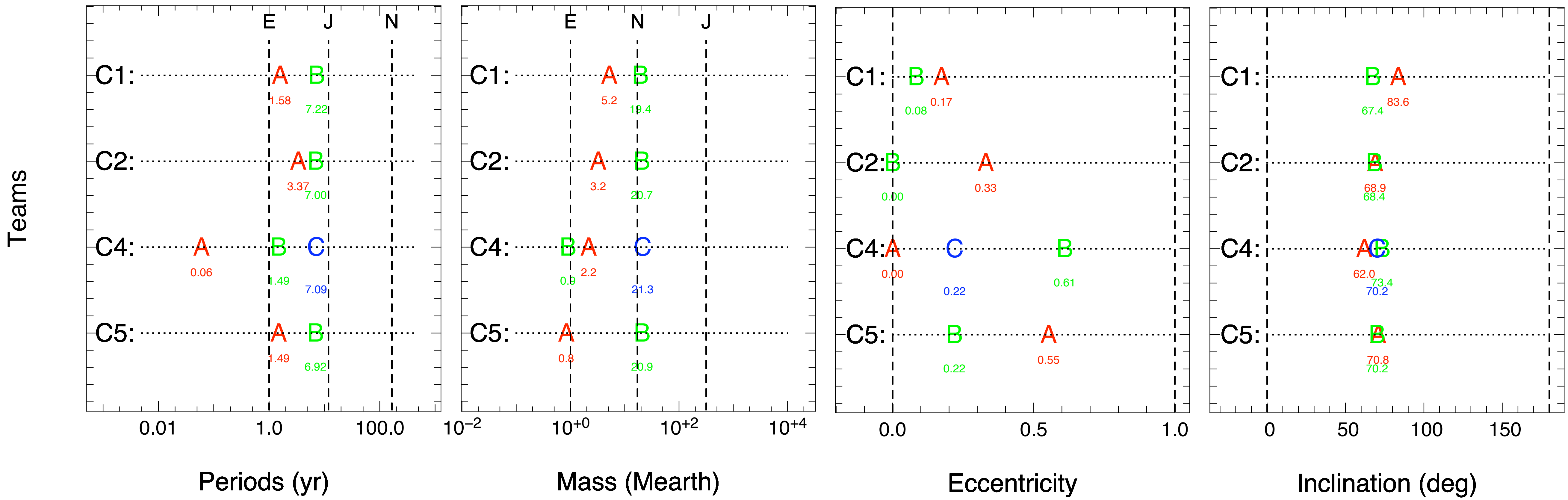
- SNR >5.8,
- period < 4 yrs for astrometry,
- period < 12 yrs for radial velocity.

	Scoring Category	Phase 1 (†)	Phase 2
Completeness [# detected / # detectable]	Terrestrial	18/20 = 90%	37/43 = 86%
	HZ	1313/13 = 100%	21/22 = 95%
	Terrestrial HZ	9(*)/9=100%	17(**)/18 = 94%
	All planets	**51/54=94%**	**63/70 = 90%**
Reliability [# detected / # claimed]	Terrestrial	25/27=93%	38/39 = 97%
	HZ	16/16=100%	20/20 = 100%
	Terrestrial HZ	12/12=100%	16/16 = 100%
	All planets	**64/67=96%**	**66/68 = 97%**

(*) All 9 T/HZ Part-1 detected planets were in multiple-planet systems.
(**)10 of the 17 T/HZ Part-2 detected planets were in multiple-planet systems.
(†) Results here are from Analysis Team C5 only; Best comparable to Part 2.

From Marr et al., Missions for Exoplanets 2009

How to choose the best solutions?

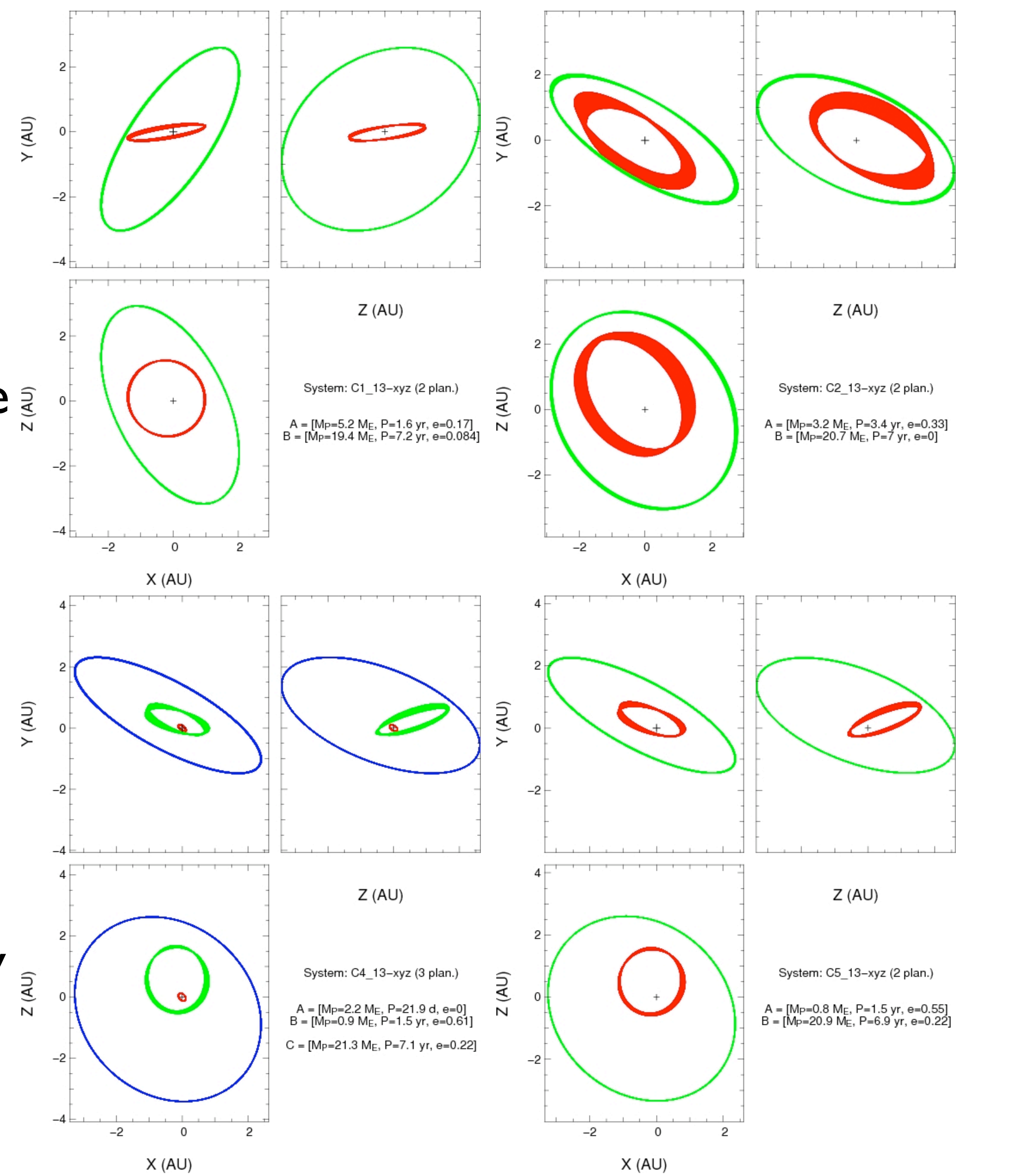


- different solutions which are all plausible
- first method is to compare χ^2
- then are some of these solutions unstable?

➡ use of a N-body code

Use of the HNBody package

- Integration of the orbit solutions
- HNBody is a symplectic integration package for hierarchical N-Body systems (version 1.0.3) developed by Rauch & Hamilton (2002).
- It integrates the motion of particles in self-gravitating systems where the total mass is dominated by a single object;
- Based on symplectic integration techniques in which two-body Keplerian motion is integrated exactly.
- HNBody is primarily designed for systems with one massive central object and has been used previously for extrasolar planet simulations (Veras & Armitage, 2006, 2005).



Stability of the orbits

Table 1: Energy errors computed by HNBody for the systems of phase 2 requiring stability inspection.

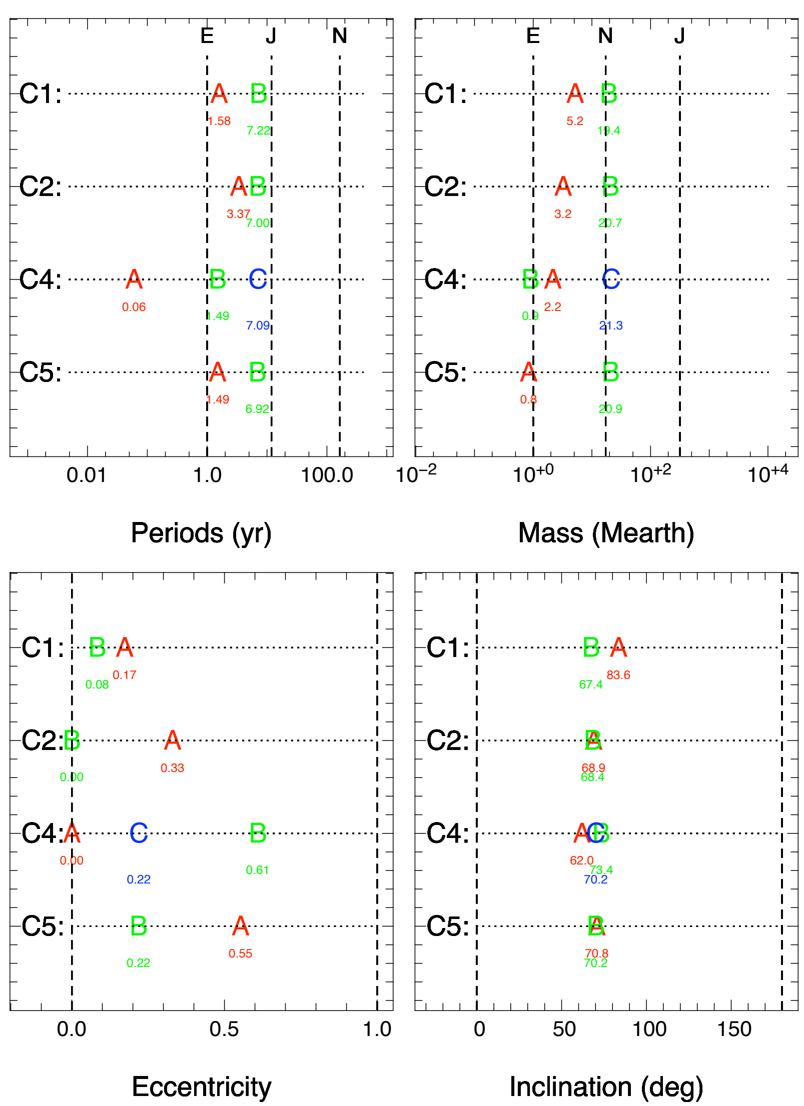
System Number	Team number	Energy errors avg	rms	max	Stable solution
Phase 2, batch #2					
#13	C1	-1.3221e-12	1.8254e-09	2.4568e-08	yes
	C2	-6.5104e-11	1.2748e-09	5.3369e-09	yes
	C4	4.6499e-13	5.3316e-13	8.2330e-13	yes
	C5	4.6348e-09	5.6051e-09	4.0843e-08	yes
Phase 2, batch #3					
#3	C1	-6.2330e-02	6.2386e-02	6.3392e-02	
	C2	-1.3049e+00	1.3884e+00	1.4746e+00	
	C4	-1.9777e-02	2.1679e-02	4.8040e-02	
	C5	-4.0915e-01	4.1067e-01	4.1277e-01	
#6	C1	1.4801e-13	1.6630e-13	2.6529e-13	yes
	C2	3.2806e-06	1.8298e-05	4.4783e-05	yes
	C4	6.6212e-02	8.4609e-02	1.9430e-01	
	C5	6.3484e-09	9.4341e-09	3.4962e-08	yes
#10	C1	2.6754e-15	8.0286e-15	2.6806e-14	yes
	C2	-2.0589e-03	3.3967e-03	9.1104e-03	
	C4	-1.3316e-09	5.4949e-09	1.6754e-08	yes
	C5	1.1024e-05	1.2969e-05	2.2789e-05	yes
#11	C1	-1.2775e-02	3.1067e-02	3.5883e-01	
	C2	-1.9176e-14	1.4812e-13	3.6292e-13	yes
	C4	-1.3741e-10	5.0808e-08	3.1649e-07	yes
	C5	-4.1552e-01	4.1800e-01	4.2261e-01	
#17	C1	4.8897e-14	6.4234e-14	1.5055e-13	yes
	C2	-1.0076e-02	1.1897e-02	2.5154e-02	
	C4	1.8256e-07	2.0393e-07	4.7879e-07	yes
	C5	3.9736e-02	4.0392e-02	4.6356e-02	

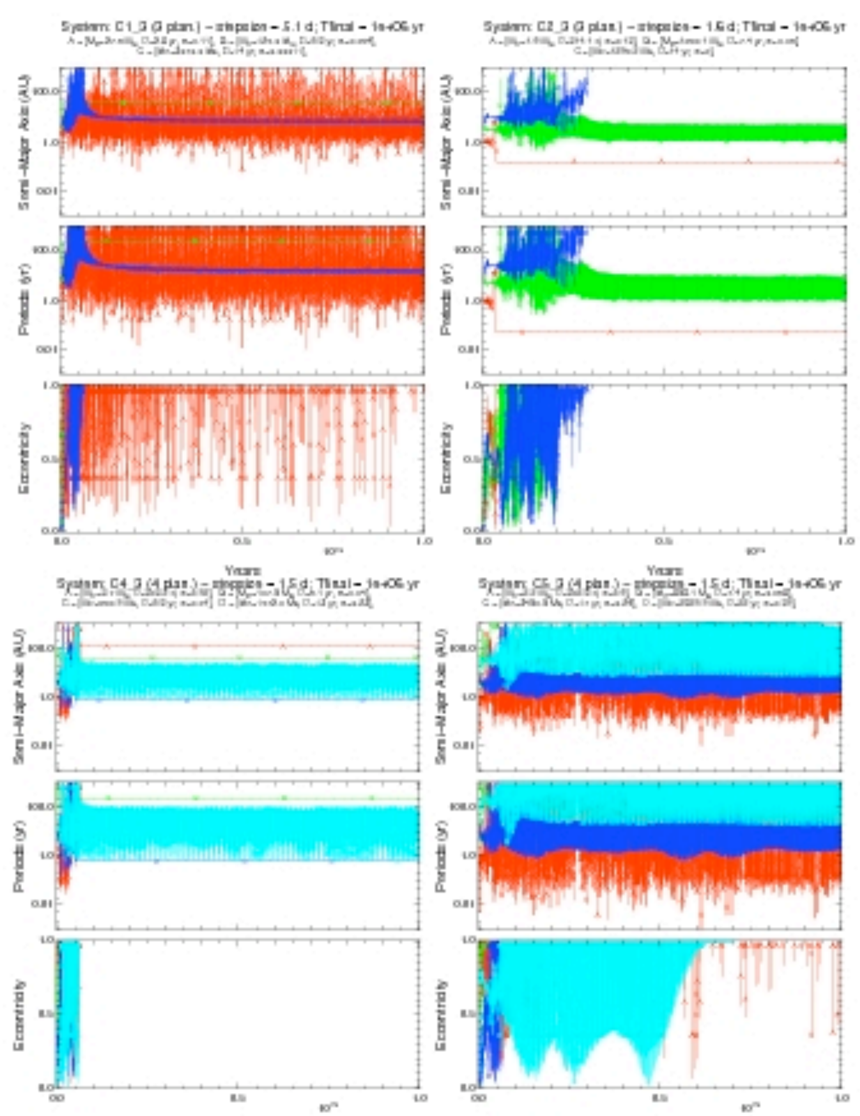
- When orbits are unstable, then HNBody does not succeed to maintain energy conservation
- The systems have to be integrated over a sufficient length of time, longer than the seculiar time
- The time sampling must be fine enough to compute correctly the small period orbits (~Pmin/200)
- It is a good criterian to rule out a solution
- However some solutions have “strange” eccentricities or inclinations that may perturb the computation.

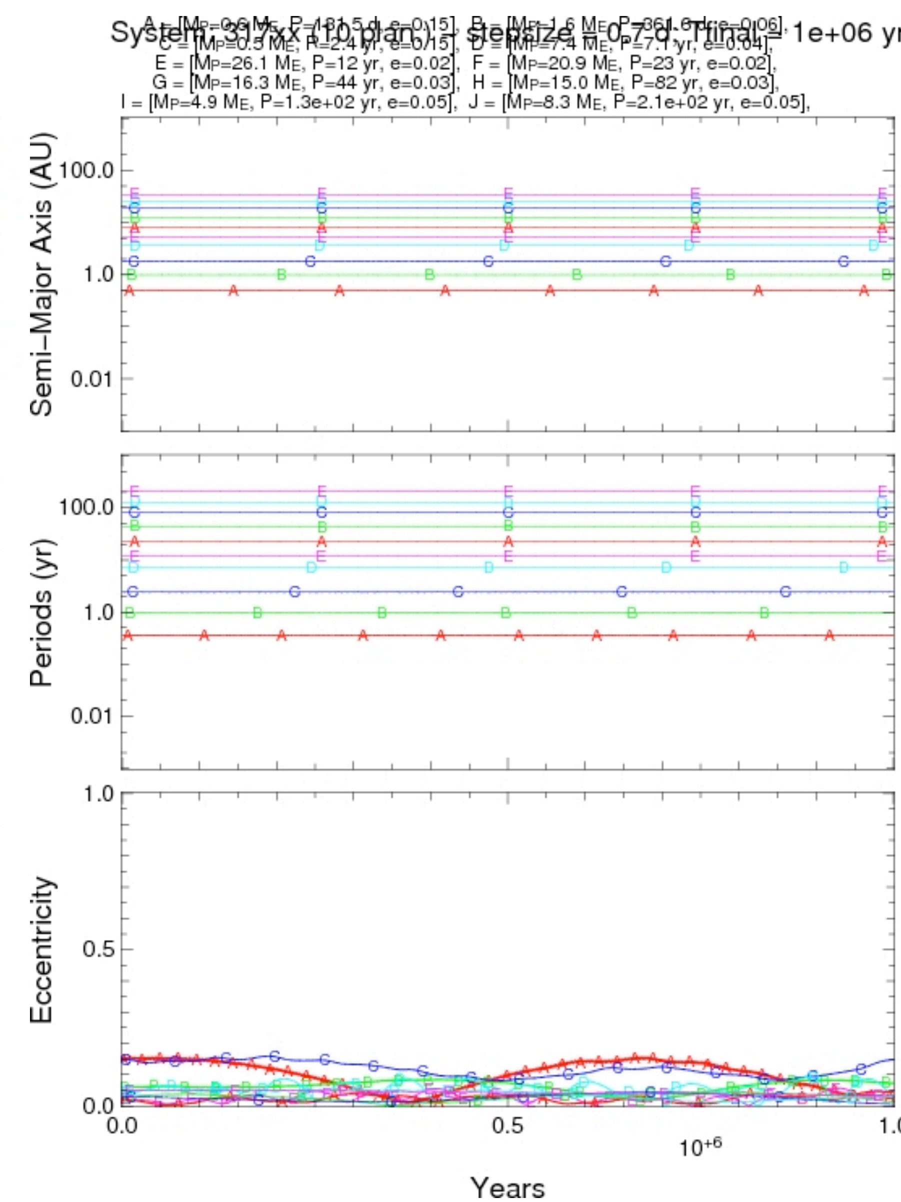
Stability of the orbits

- Even if a solution is found stable, the evolution of parameters might appear to diverge (see system 13 batch2, below).
- A system might appear unstable because all planets of the systems have not been discovered

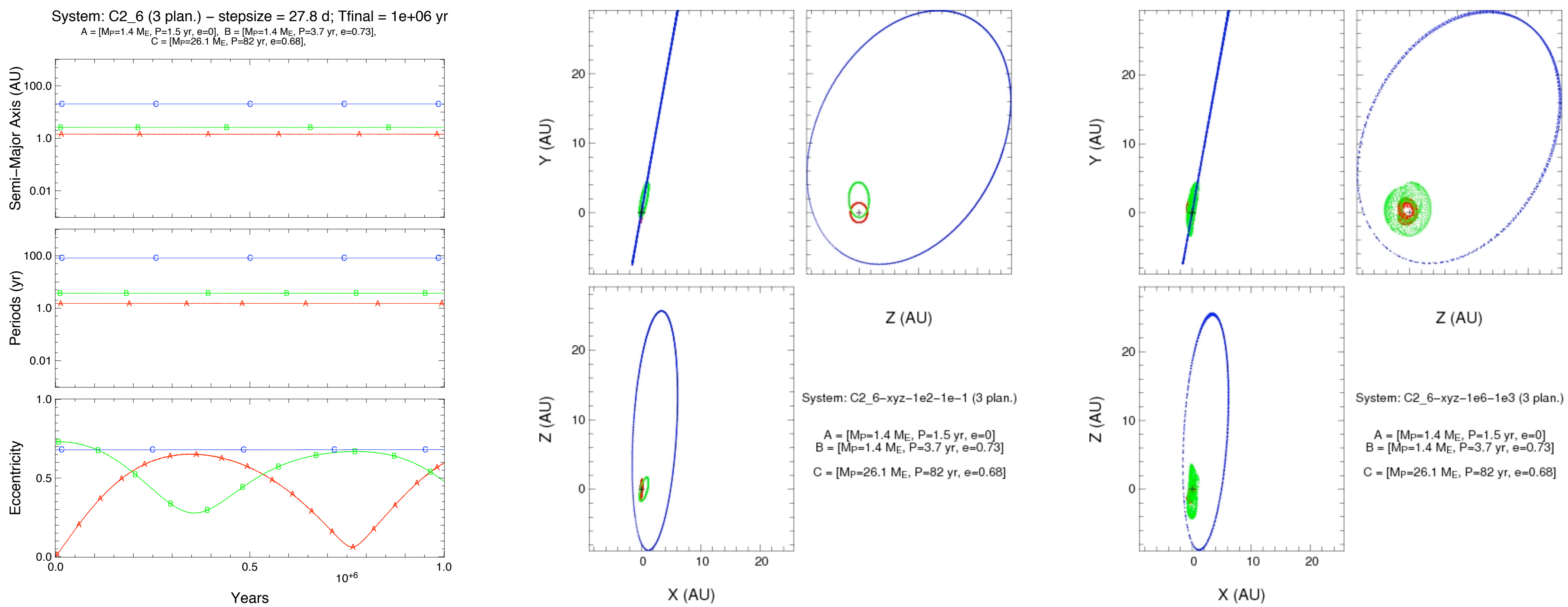
Team solutions Batch2 – System: #13 – 0.69 Mo (2/2/3/2 planets)







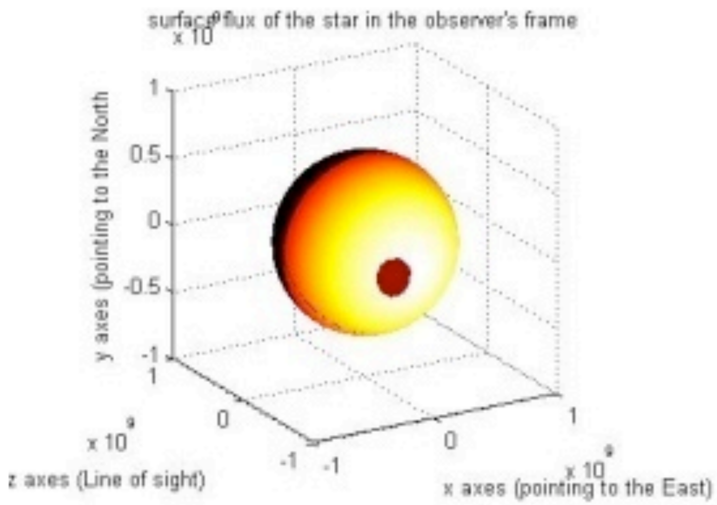
Some "strange" solutions however stable



- There can be cyclic evolution of the parameters
- The distance star-planet can cross
- Is it a criterion to reject the solution?

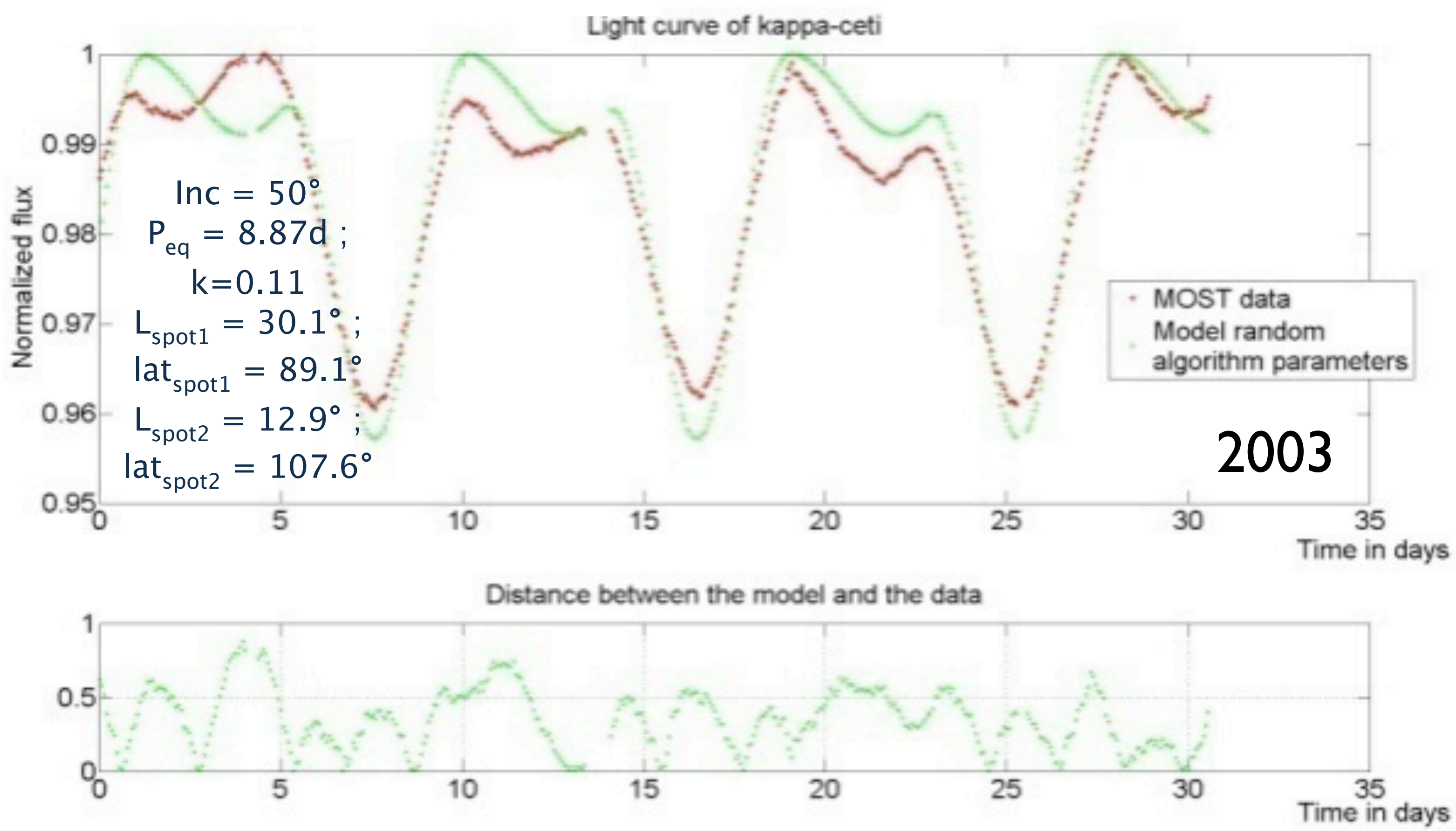
More studies are required (SURP grant approved, Catanzarite, Malhotra, Zhai, Malbet & Shao)

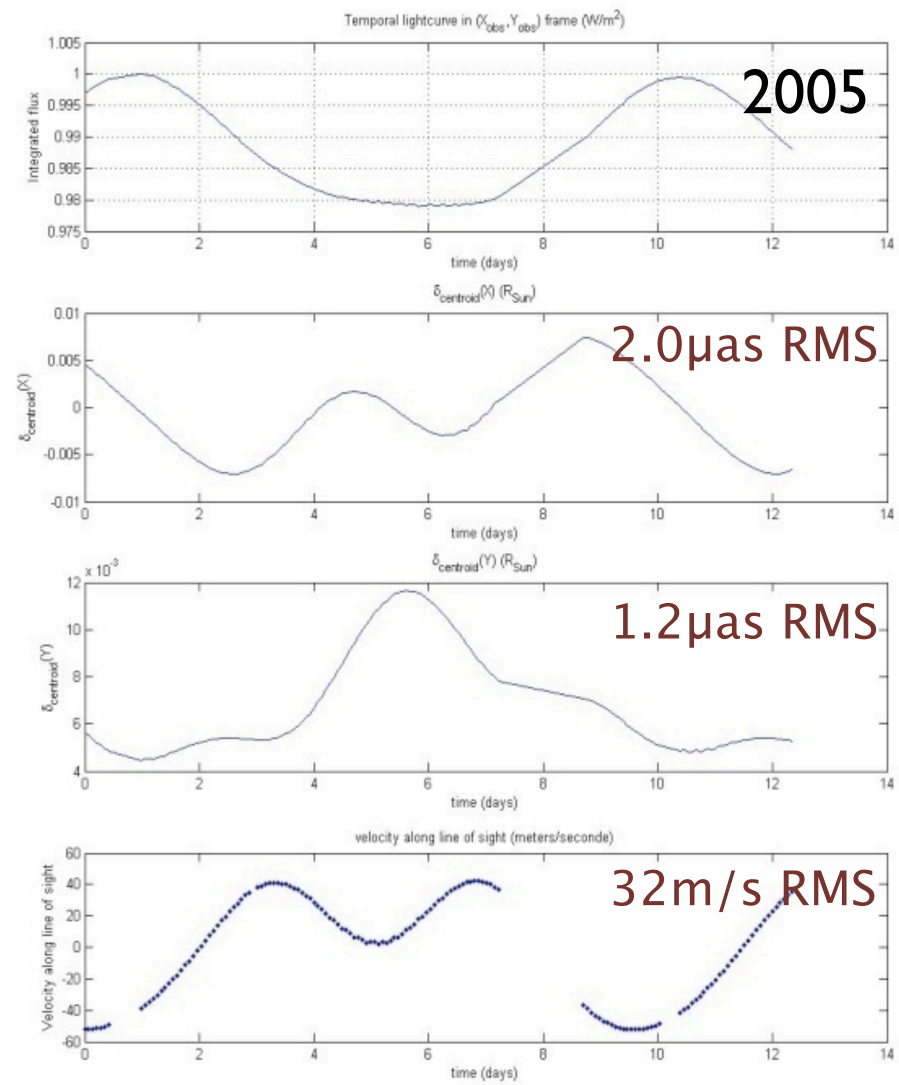
Stellar activity



Kappa Ceti

Lebreton (2009)





- Reproduce well the photometric fluctuations
- RV and astrometry signals not negligible
- RVcorrespond to Kappa Ceti RV measurements (29m/s RMS)

Perspectives

- Finding habitable Eaths with SIM seems to be within range
- Now need to simulate SIM-like data (delays, refs stars,...)
- Continue orbit integration to an additional tool to analyze the solutions (SURP)
- Same double blind study including the stellar noise
- Astrometry is less sensitive than RV to stellar noise, but still it is not negligible
- Study the photometric fluctuations of SIM stars to estimate the expected astrometry signal from the stelalr activity

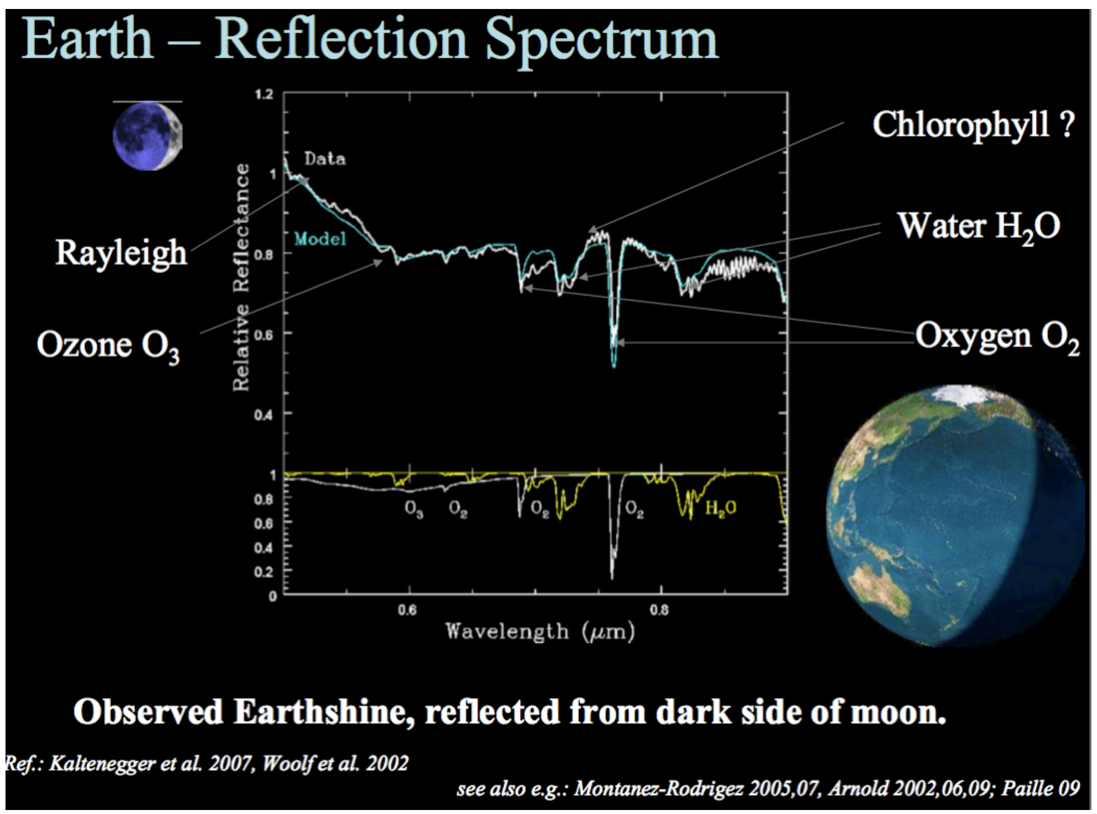
Direct imaging technique

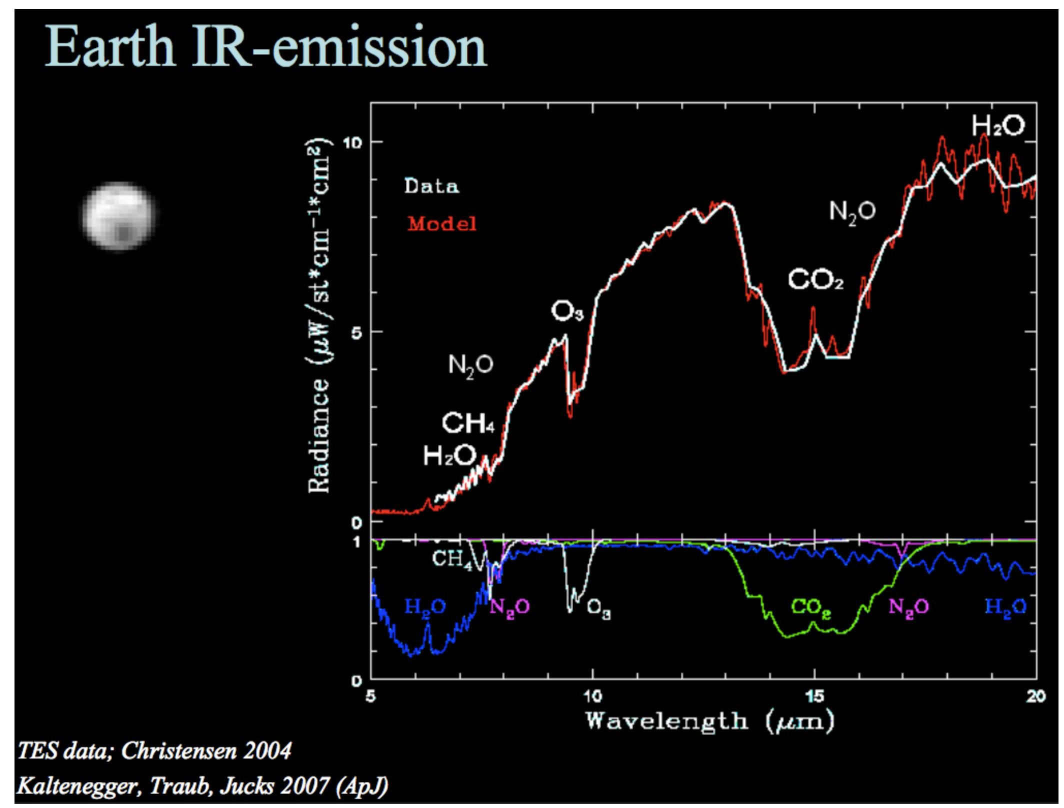
APEP with J. Sandhu, M. Shao, J. Shen, P. Lawson, G. Vasicht and APEP team

Keck nuller with R. Millan-Gabet

Rationale

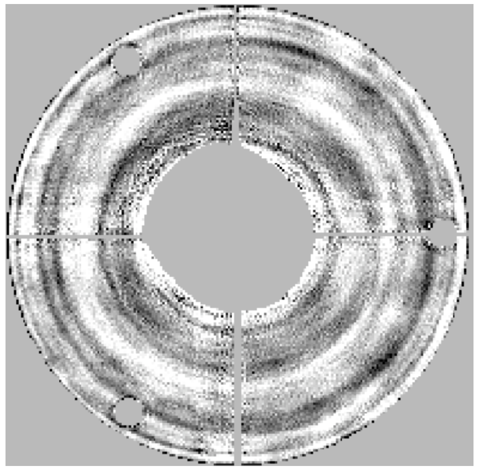
- After a number of Earth-like planets in the habitable zone will be detected, one will want to get a spectrum to identify bio-signatures



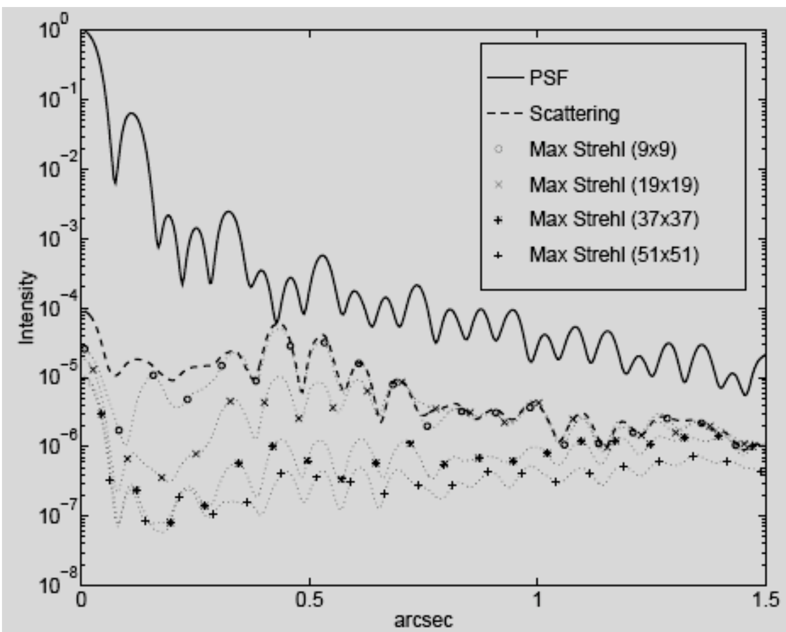


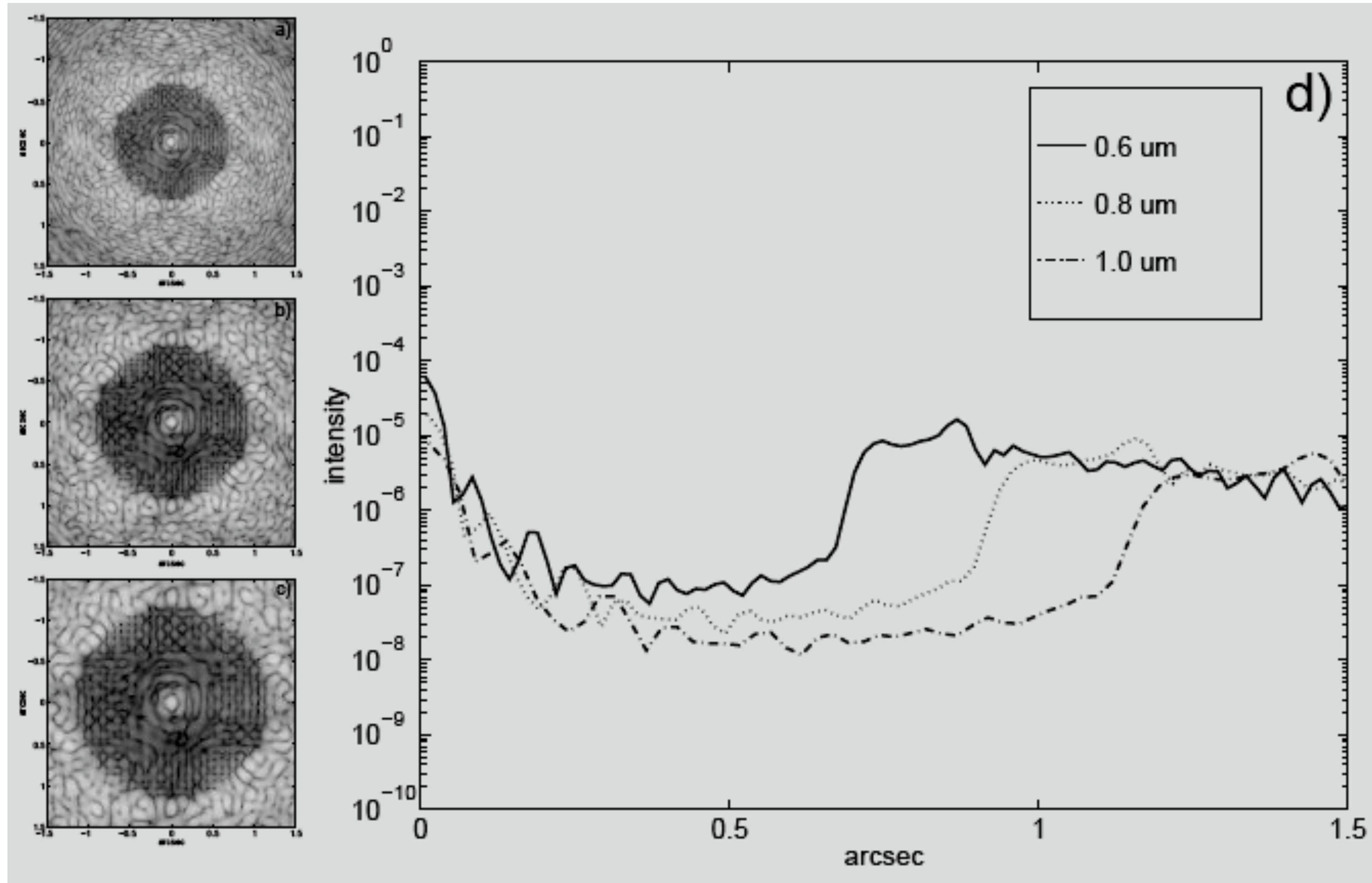
- In the visible, the need is for coronographic techniques. In the IR, the need is for nulling.

Phase effects in coronography



Hubble Space Telescope phase residuals

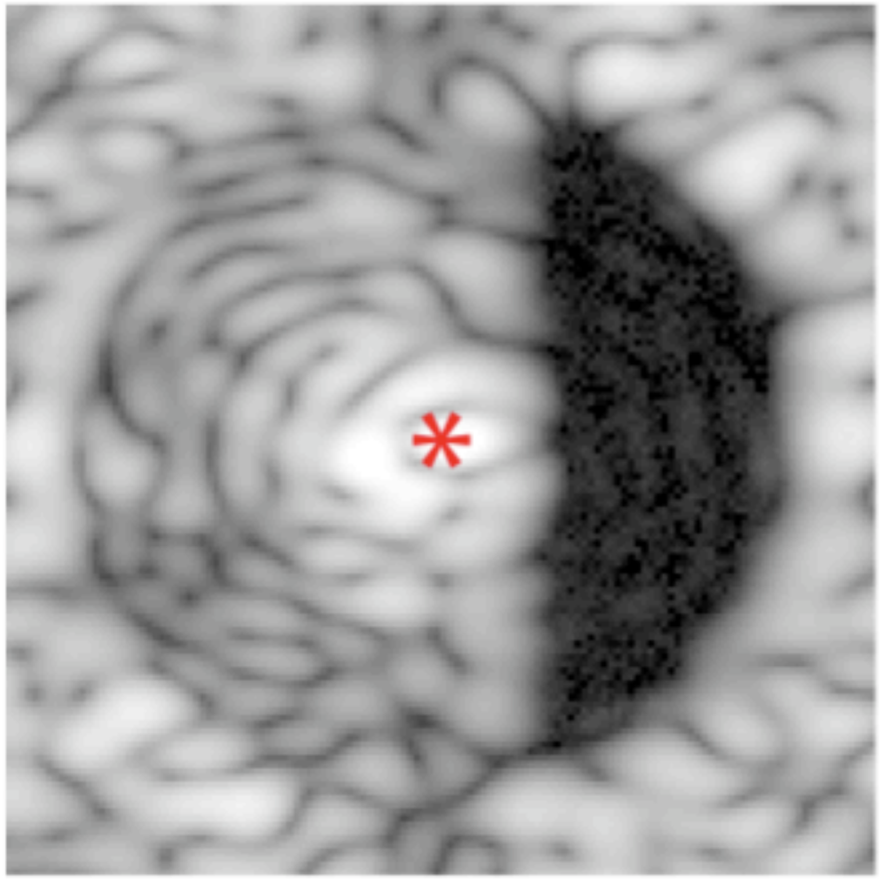


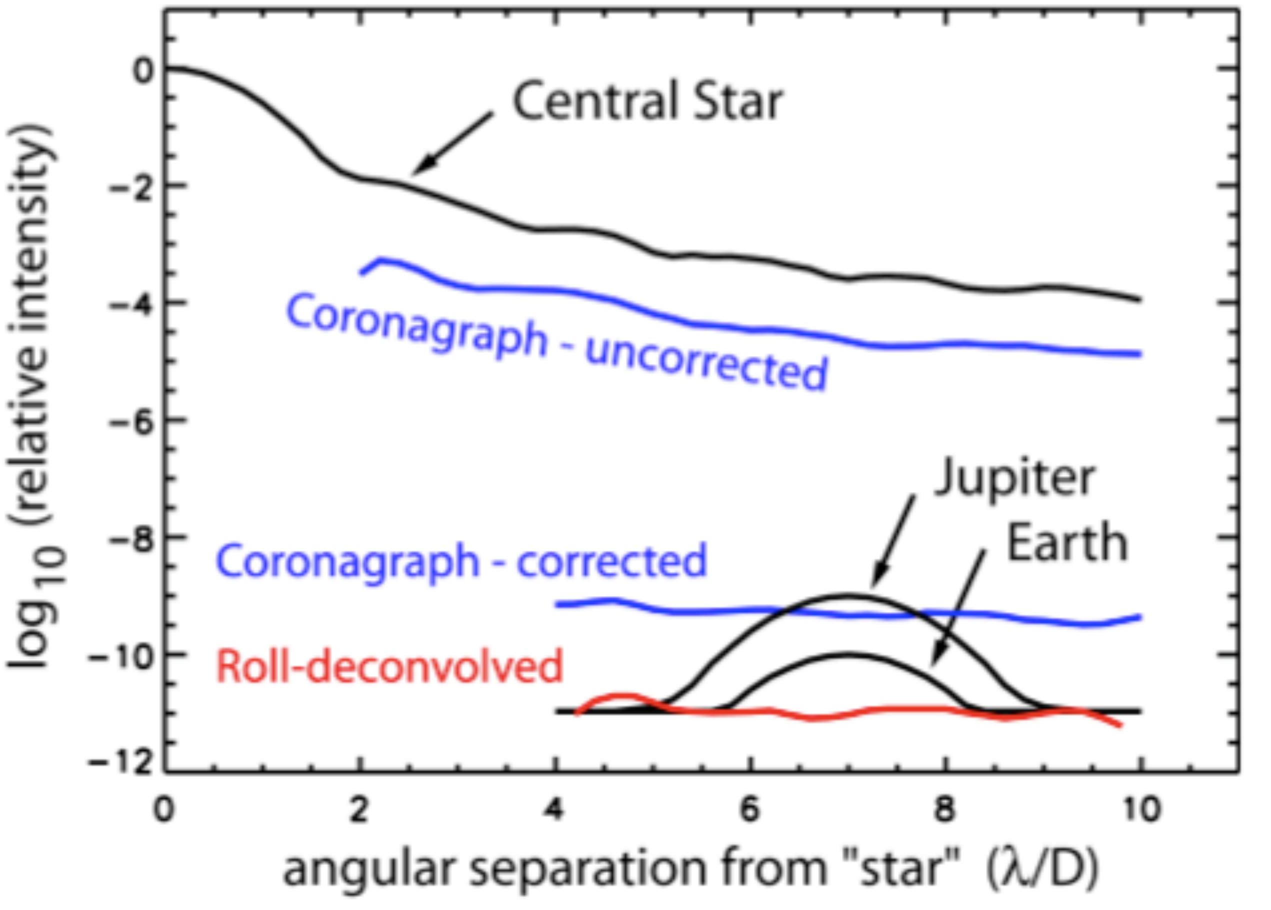


Malbet, Yu & Shao (1995)

- Various coronographic techniques can cancel out the light
- Phase effects are important when aiming at >1e5 contrast
- Dark hole algorithm developed to create zones of the image where the residuals are lower.
- Sub-nanometer WFS sensing required (0.1-1nm)
- Speckle nulling technique (Bordé & Traub 2006) has improved the result

Demonstrated in lab



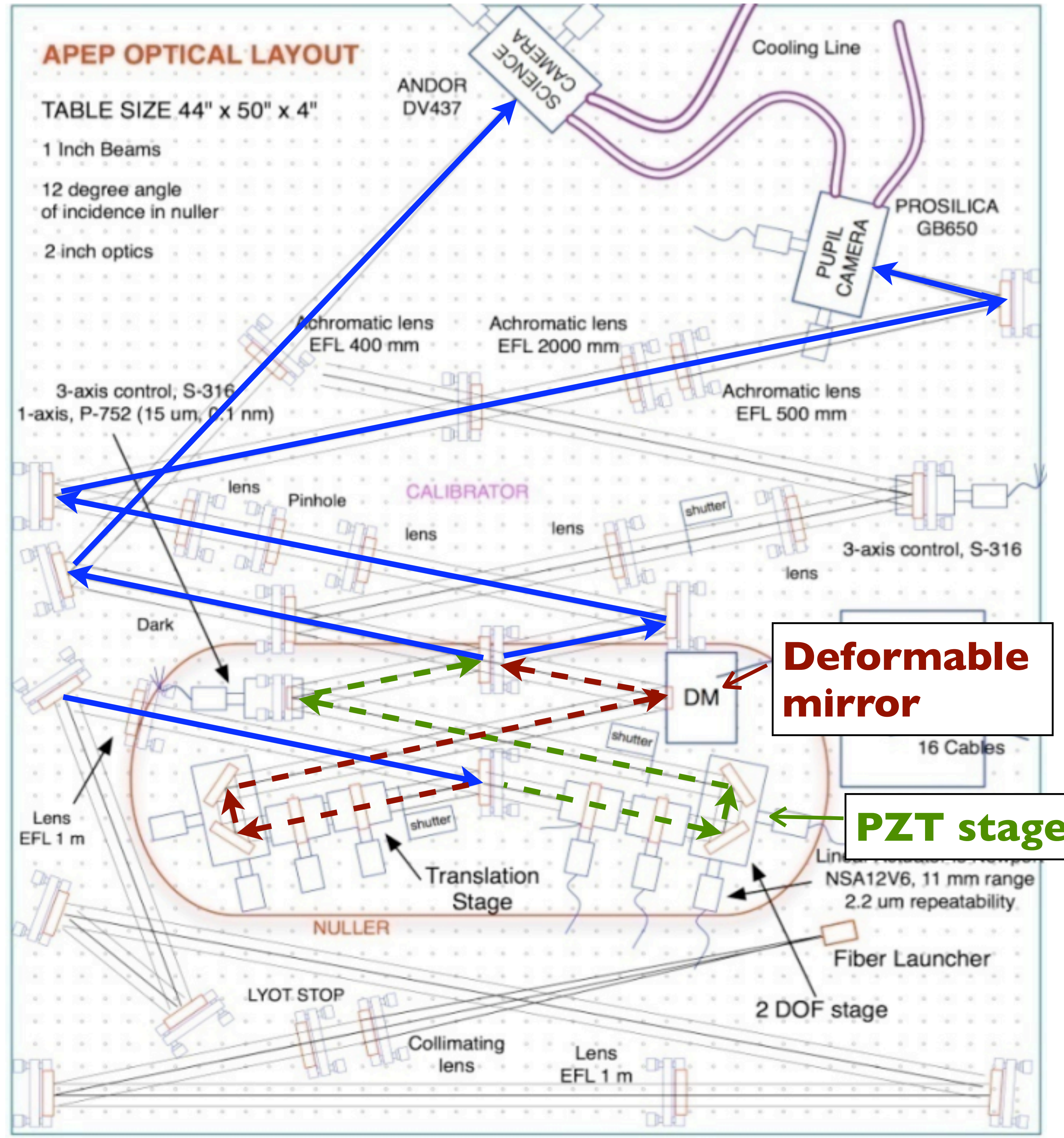


Trauger & Traub (2007, Nature 446, 771)

- contrast of 6×10^{-10} has been achieved with a 32x32 deformable mirror
- ultimate contrast of 10^{-11} obtained with additional image processing
- Inner working angle of coronograph is limited to 65 mas for TPF-C
- Nuller technique proposed in EPIC and DAVINCI allow smaller IWA but with lower throughput

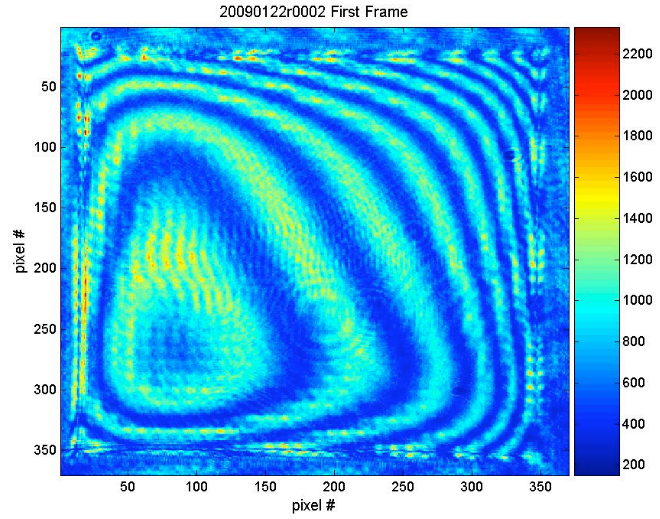
DAVINCI and EPIC: visible nuller

- A testbed (APEP) has been designed to measure the performance of a visible nuller (for DAVINCI & EPIC)
- It includes a deformable mirror (DM) in one arm, and a PZT stage in the other arm.
- There is a science camera in the image plane and a pupil camera.
- PZT generate ABCD(E) signal for wavefront sensing
- DM correct the phase

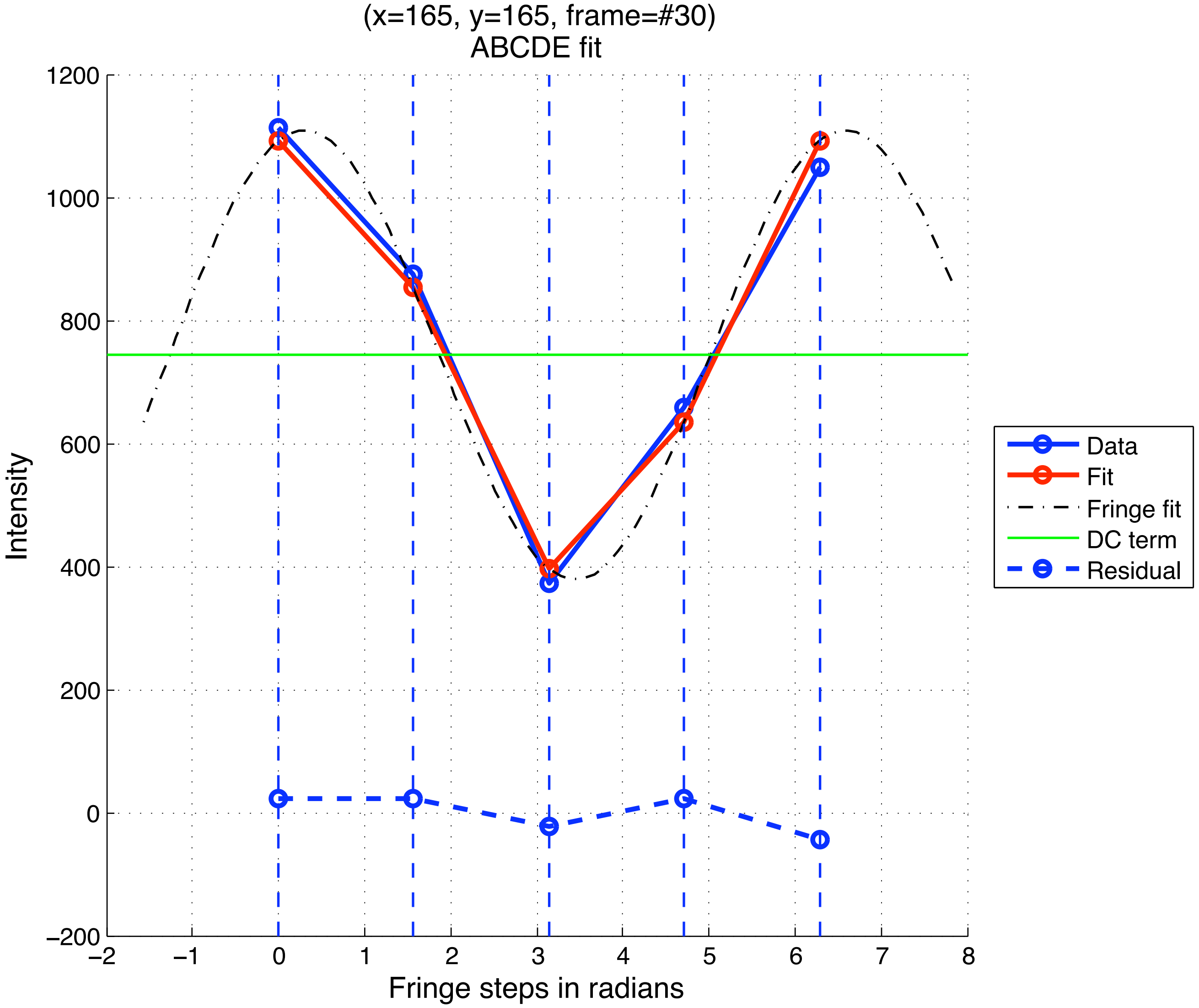


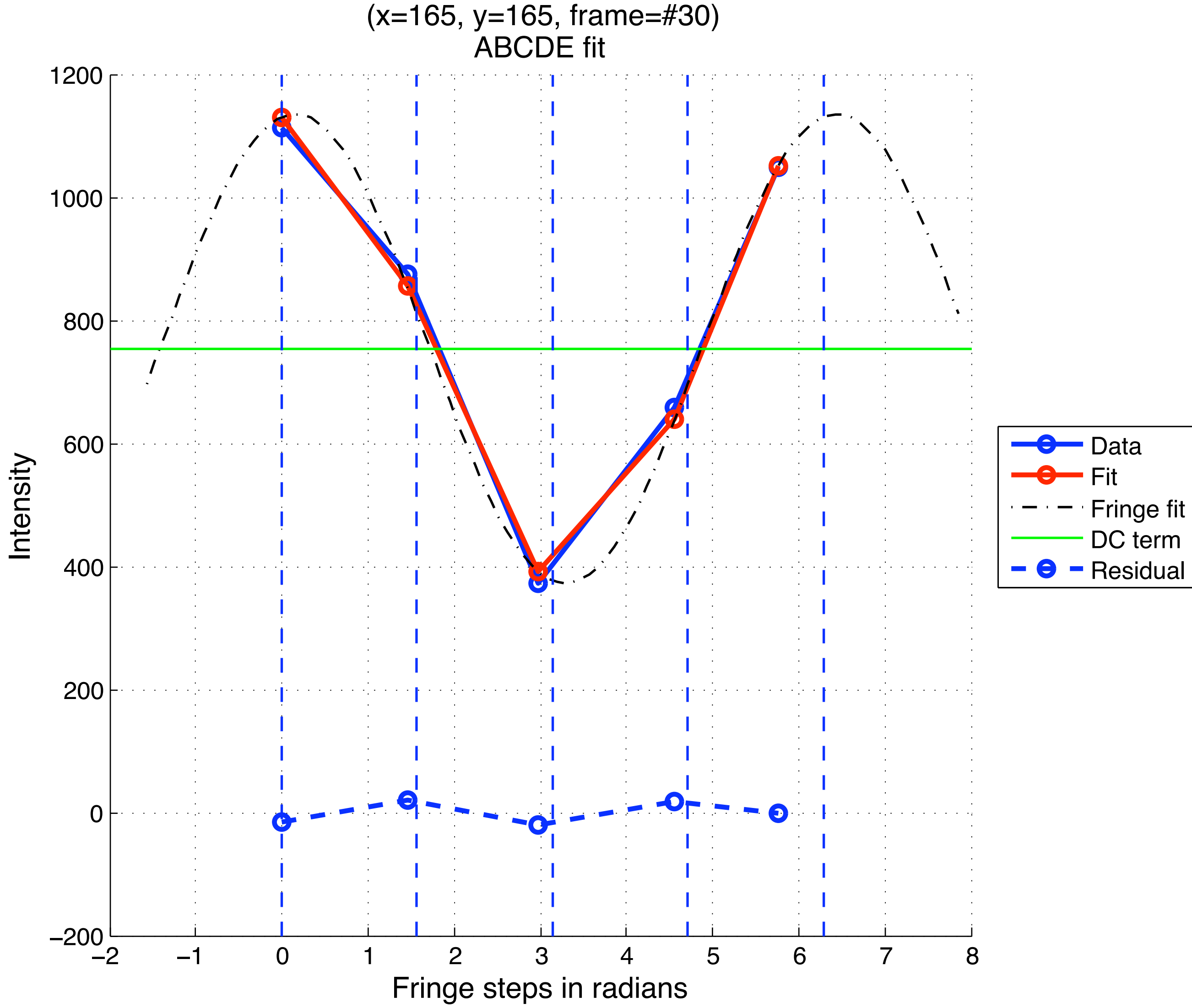
Measuring the pupil wavefront at the nanometer level

- ABCDE fringe measurements
- Linear fit and non linear with piston errors

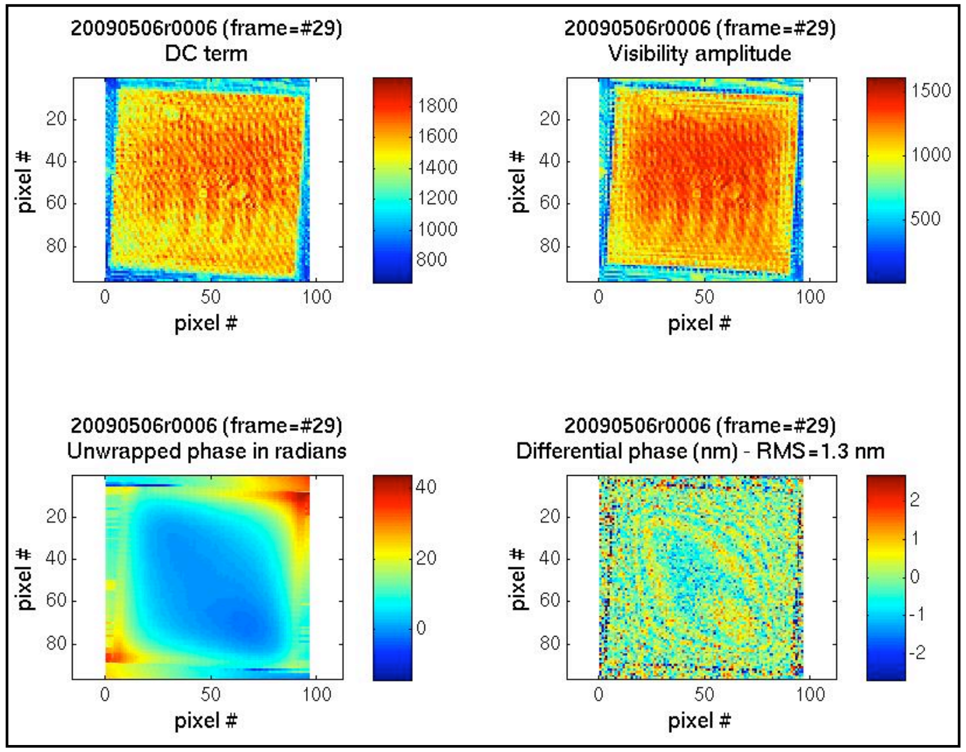


First frame

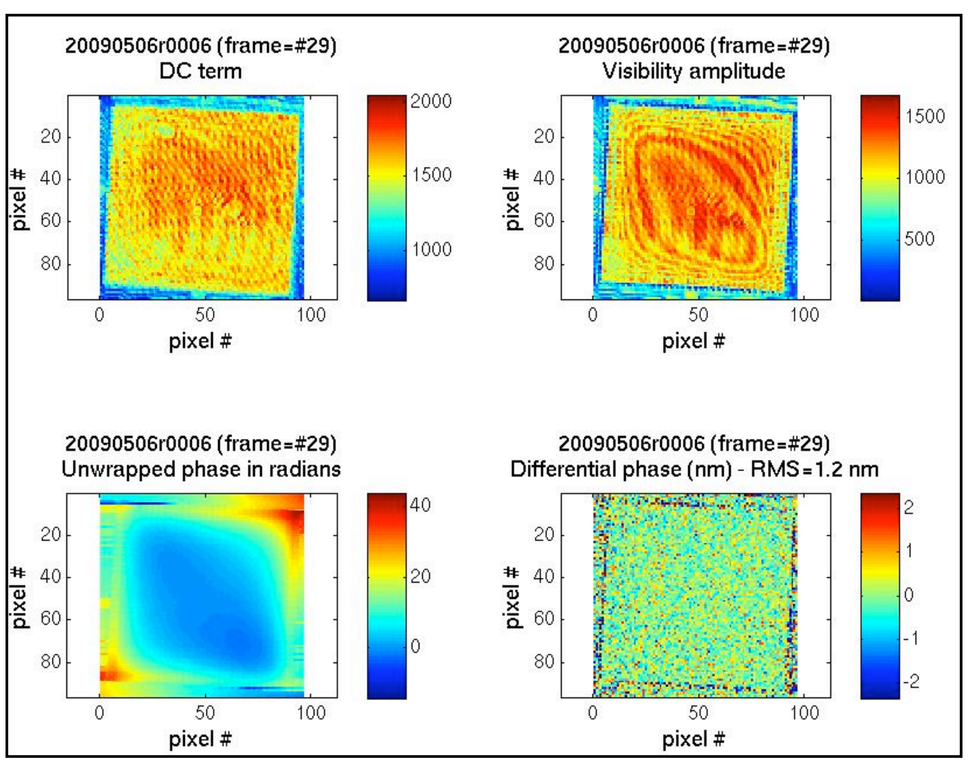




Performance of linear and non-linear estimators

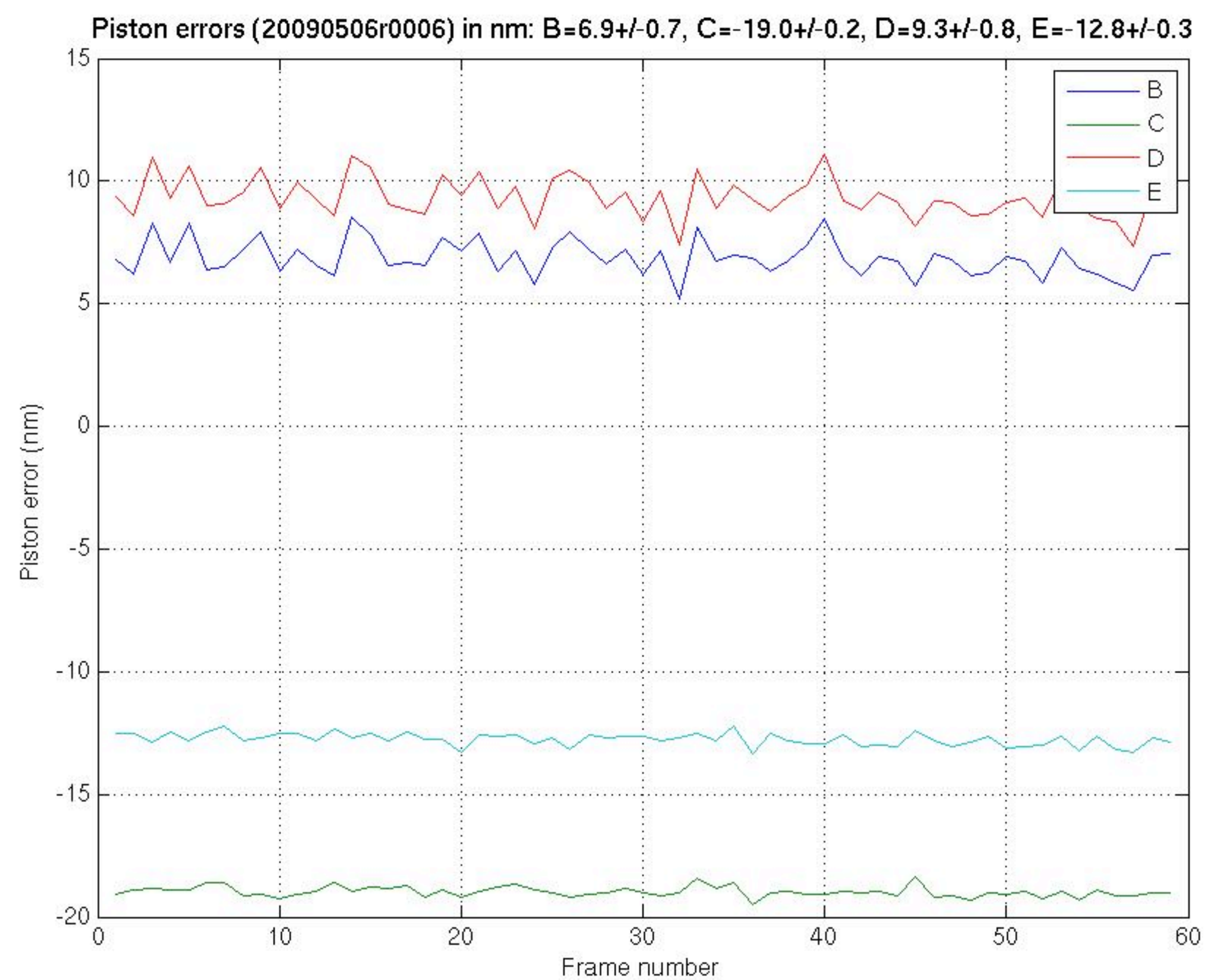


Linear estimator

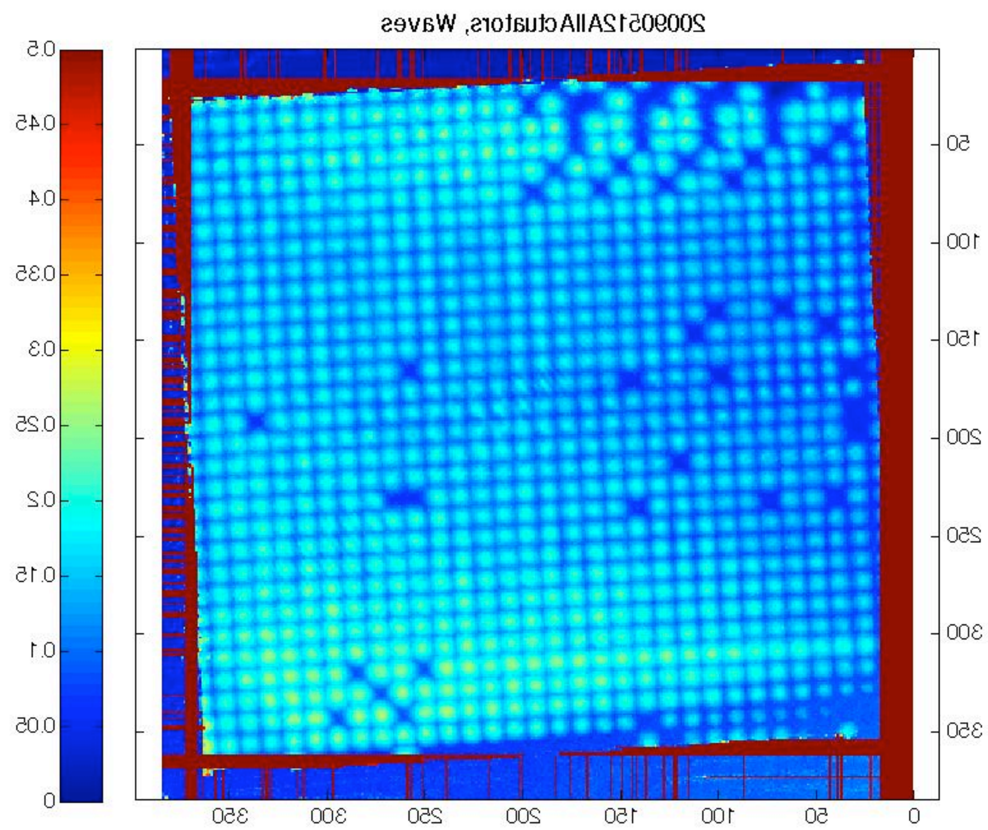


Non linear estimator

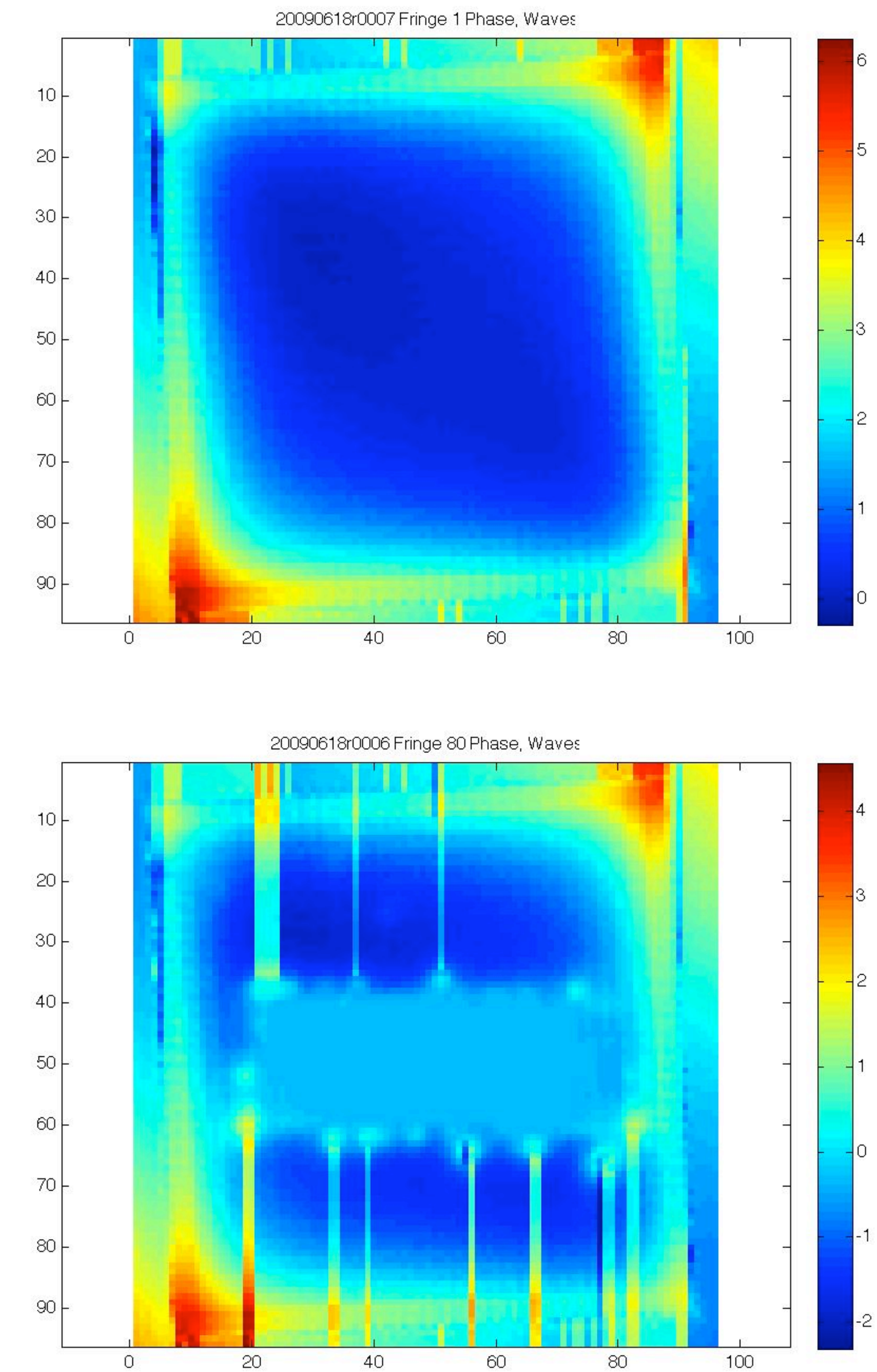
- Linear estimator is faster and can give a first estimation
- Non linear estimator can give better precision and no cyclic errors
- Limited micro-turbulence => vacuum chamber



Servo control



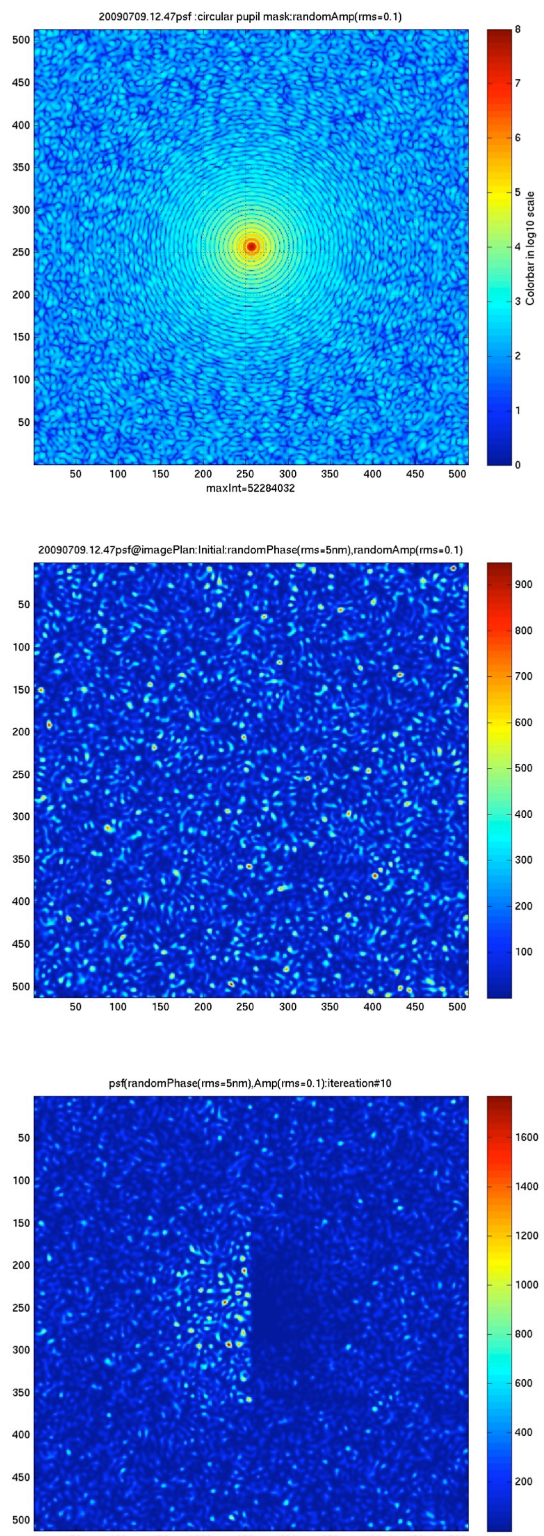
Deformable mirror



Flattening the wavefront
(courtesy of J. Sandhu)

- Simple matrix servo the DM with off-load on the 3-axis PZT
- Still in the first phase
- Issues with the Lyot stops and dead actuators

Toward the dark holes



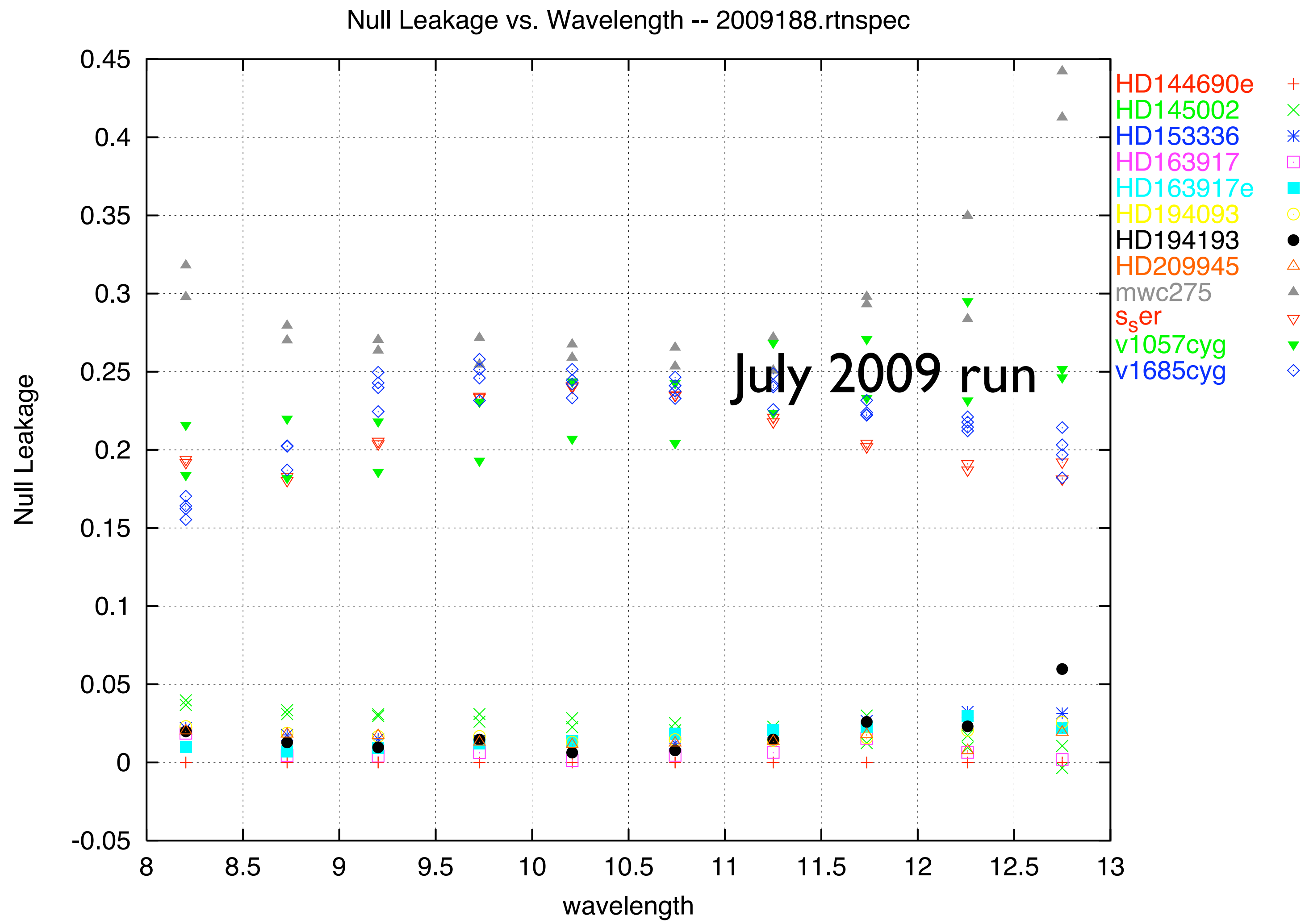
Courtesy of J. Shen

- Only simulations for the moment
- First step is to find the best null, then to manage the dark hole by computing the phase that zeroes the dark region
- Need to control the amplitude (use of fiber-bundle) if not the hole will be centro-symmetric
- There exists in APEP a calibration system for non common path errors.

Keck nuller

- Proposal "A Comprehensive study of the planet formation zone: Probing the inner pre-planetary disk using multi-wavelength observations with the Keck Interferometer." by Millan-Gabet et al.

- 1.5 nights in 2009A and 2 nights in 2009B



➡ The Keck nuller is an excellent demonstration of TPF-I

Strategy to reach the goal of habitable Earths

with C. Beichman, R. Goullioud, M. Shao, S. Unwin, J. Marr, V. Coudé du Foresto

The BLUE DOTS initiative

- Contribute to building a community in Europe around the exoplanets theme
- Recognizing that the ultimate science goal (characterization of habitable exoplanet atmospheres) will require several intermediate steps…
- Converge towards a strategy enabling a more coherent approach to calls for proposals in ground and space based projects...

From Coude du Foresto (2009, Missions to Exoplanets)

Exoplanet detection methods

A step by step approach

(Science Potential Levels):

[★] Statistical study of planetary objects

[★ ★] Designate sources suitable for spectroscopic follow-up

[★ ★ ★] Carry out spectroscopic characterization

These define different science potential levels which can be achieved on different object classes => different difficulties

Methods:

– RV: Radial Velocities
– µlensing
– Transit photometry
– Astrometry
– Multiple Aperture Imaging
– Single Aperture Imaging

Scales:

– E (existing)
– G (30M€, 5 years)
– M (450M€, 10 years)
– L (650M€, 15 years)
– XL (> 1G€, > 20 years)

	Hot Giant Planets (young or hot)	Other Giant Planets (same as in Solar System)	Hot Terrestrial Planets (hot, young or super-Earth)	Telluric Planet in habitable zone around M-dwarfs	Telluric Planet in habitable zone around solar-type stars
µlensing		★	★	★	★
Radial velocities	★ ★	★ ★	★ ★	★ ★	☆☆
Transits	★ ★ ★	☆ ☆	☆ ☆ ☆	★	★
Astrometry	★ ★	★ ★	★ ★		★ ★
V imaging / coronagraphy	★ ★ ★	★ ★ ★		★ ★ ★	★ ★ ★
IR imaging / nulling	★ ★ ★		★ ★ ★	★ ★ ★	★ ★ ★

What do we want to know ?

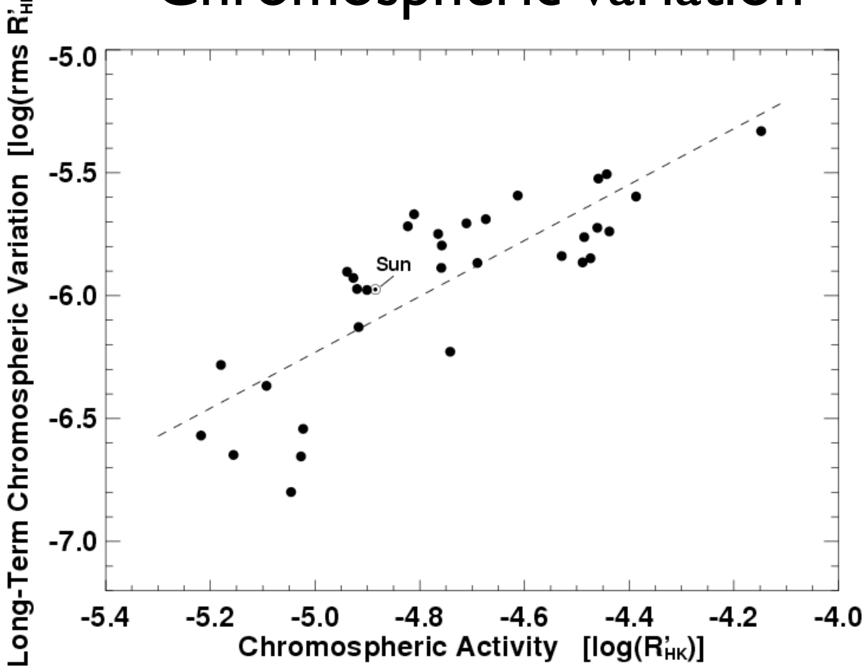
- ✓ Habitability criteria
- ✓ Planetary atmospheres & surfaces
- ✓ Formation & evolution of planetary systems
- ✓ Targets & their environments

- *Cornerstone questions:*
  - *Can telluric habitable planets be identified from the ground by RV ?*
  - *Should we search for habitable planets around M stars ?*
  - *Is spectroscopic characterization of the atmosphere of telluric exoplanets possible by transit spectroscopy ?*
  - *Do we need to solve the exozodi issue ? If yes, how best to solve it ?*

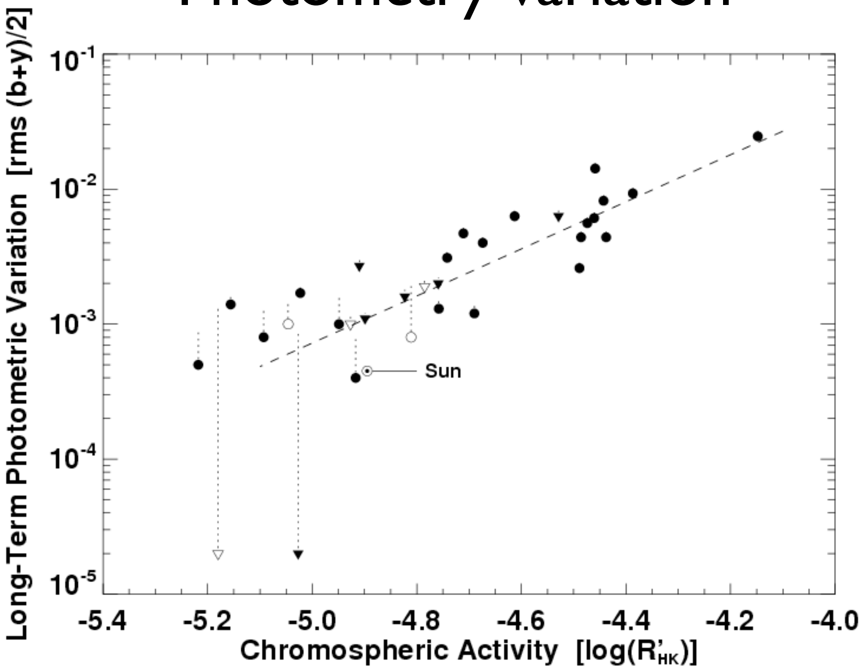
Radial Velocities & Astrometry

- Debate at the Blue Dot Meeting #6 in Bern
- M. Shao (astrometry, SIM) and S. Udry (RV, ESPRESSO)
- Issues:
  - Noise level required: 0.05µas/0.3µas for astrometry, few $cm.s^{-1}$/9$cm.s^{-1}$ for RV
  - Instrumental limitations: 0.035µas for SIM, 10 cm/s for ESPRESSO for V<8
  - Stellar noise: stellar spots on Sun @ 10pc gives: 0.08µas and 0.45m/s
  - Correlated noise: stellar spots life time of ~ 1week?
  - How quiet is the Sun? Stars quieter than Sun: 10%-15% for Shao, 50% for Udry

Chromospheric variation



Photometry variation



Lockwood et al. (2007, ApJS, 171, 260)

Radial Velocities & Astrometry (2)

- Issues (cont'd):
- RV strategy for Earth-like planets with VLT: 50-70 stars, 100 RV/star, 4-5 nightsm/star
- Look for M-stars in IR with laser comb (higher signal)
- Astrometry will look at 60-100 Earth-like planets in the habitable zone of a star in the solar neighborhood
- Spectroscopic follow-up for detection of biosignatures requires **Earth-like planets in the habitable zone of a solar-type star in the solar neighborhood (<15pc)**

- Conclusion:
- RV and astrometry have both the capability to detect Earth around stars
- ESPRESSO has the capability to detect merely a few 4-5 $M_\oplus$ candidates within the inner 15 pc of the solar neighborhood
- SIM can survey the 60 closest solar-type stars and has the capability to detect down to 0.8 $M_\oplus$ planets

There is consensus that the RV approach should be followed even if there is a limited chance of finding appropriate habitable Earths at an accessible distance, because nobody wants to miss such a system. However for the identification of Earth-like systems for a spectroscopic follow-up for bio-signatures detection, astrometry is probably required to ensure a result but is also more expensive.

http://www.pathways2009.net

Setting up a collaboration JPL/CNES...then ESA?

- Proposal to contribute to SIM at CNES (Léger & Malbet, April 2008)
- List of possible deliverables (Goullioud & Marr Sep 2008): E2V detectors, delay line, siderostats,...
- Scientific workshop with the French community (Feb 2009)
- Informal meeting with CNES technical staff and French space lab (Sep 2009)
- Satellite meeting in Barcelona (Sep 2009): *Opportunities with SIM-Lite*
- ...and maybe the beginning of a European contribution?

Conclusions

Summary

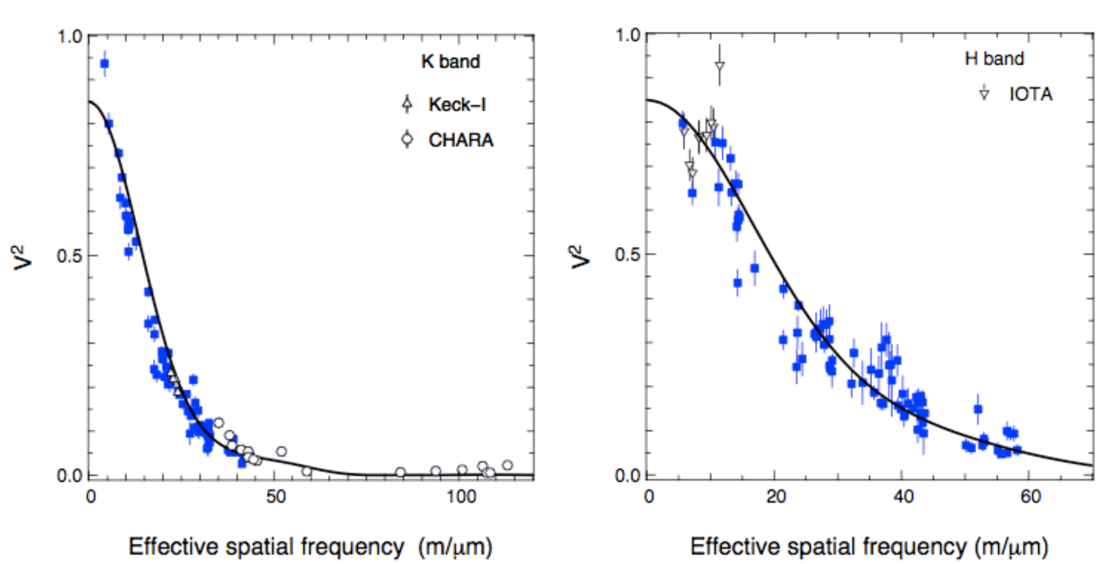
- Orbit integration of SIM astrometry solutions and effect of stellar noise
- Non-linear LSQ algorithm for wavefront sensing in the APEP visible nuller
- Keck interferometry nuller observations of young stars
- Blue dot initiative helps to give answers to specific questions and draw a framework

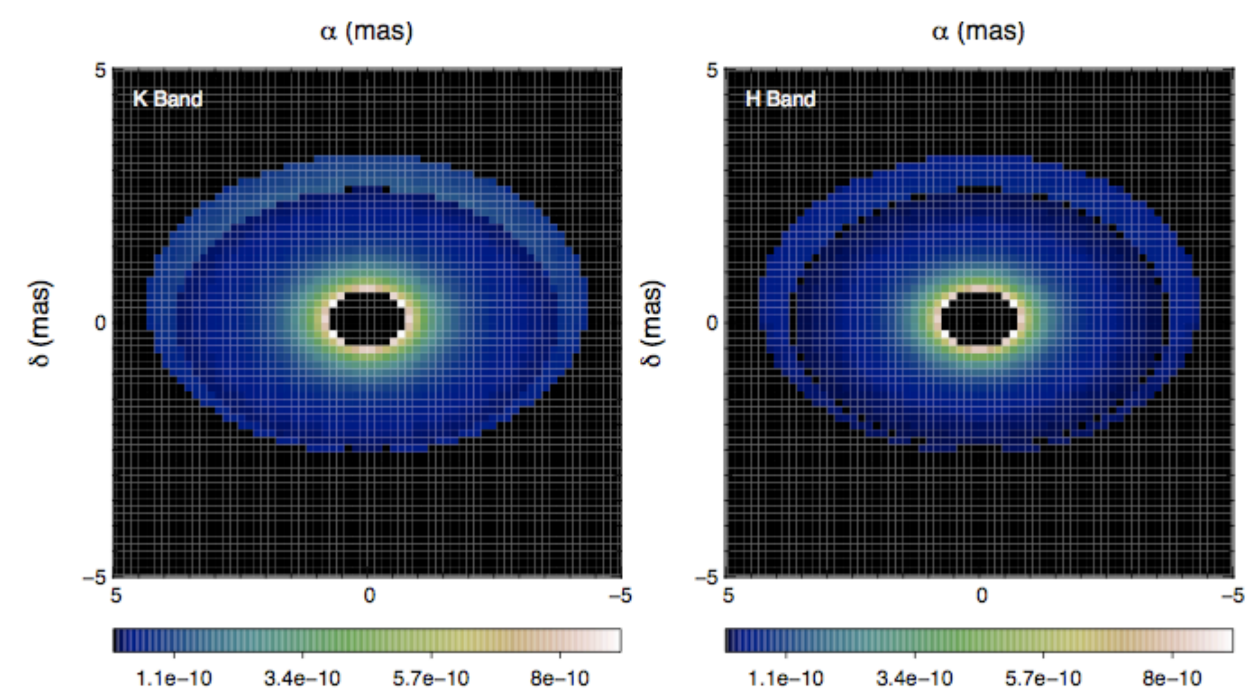
Other works

- "dark fringes" experiment: *phase closure nulling* (see seminar in Oct 2008 and Chelli et al. 2009)
  - Observing tests on CHARA (Malbet, Millan-Gabet et al.)

- Observations of protoplanetary environments around young stars with AMBER/VLTI: e.g. MWC 275

Benisty et al. submitted





- Interferometry synthesis: Image reconstruction